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AD-A179 084

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Test Operations Procedure 1-1-010	5. MONITORING ORGANIZATION REPORT NUMBER(S) same as item 4
6a. NAME OF PERFORMING ORGANIZATION U.S. ARMY COMBAT SYSTEMS TEST ACTIVITY; 6b. OFFICE SYMBOL (If applicable) STECS-AD	7a. NAME OF MONITORING ORGANIZATION U.S. ARMY TEST & EVALUATION COMMAND
6c. ADDRESS (City, State, and ZIP Code) ABERDEEN PROVING GROUND, MARYLAND 21005-5059	7b. ADDRESS (City, State, and ZIP Code) ABERDEEN PROVING GROUND, MD 21005-5055
8a. NAME OF FUNDING/SPONSORING ORGANIZATION (same as item 7a); 8b. OFFICE SYMBOL (If applicable) AMSTE-TC-M	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) (same as item 7b)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
AMC-R	310-6		

11. TITLE (Include Security Classification)

"VEHICLE TEST COURSE SEVERITY"

12. PERSONAL AUTHOR(S)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM ______ TO ______	6 April 1987	19

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Automotive test course, Roughness of roads, Test facilities, Power spectral density, Test course severity, Profilometer, Vehicle test course

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Provides a method of evaluating vehicle test course severity by committee assessment using accelerometers and by spectral analysis of course irregularities. Describes use of profilometer and conversion of profilometer data to power spectral density curves. Includes power spectral densities of vehicle endurance test courses at APG.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE*

AMSTE-RP-702-100
Test Operations Procedure 1-1-010 6 April 1987
AD No.

VEHICLE TEST COURSE SEVERITY

Page

1. SCOPE. This TOP describes methods for evaluating vehicle test course severity by committee assessment using accelerometers and by spectral analysis of course irregularities. Describes use of profilometer and conversion of profilometer data to power spectral density (PSD) curves. Includes power spectral densities of vehicle endurance test courses at APG. Characteristic curves of APG endurance test courses, which were developed using the PSD method of measurement provide a quantitative measure of course condition for assessing and comparing course severity.

There are about 65 km (40 mi) of unimproved and secondary road test courses at APG, on which automotive equipment is tested for endurance. Consistent course severity is essential to properly evaluate and compare reliability and durability data obtained years apart. Test course severity may change weekly or hourly, depending on weather conditions and traffic density. Each course has its own peculiarities. One test course portion may become more severe with traffic and less severe during poor weather conditions; another may degrade under both conditions; while still another may not be affected at all. All road surfaces therefore require continual inspection and maintenance.

*This TOP supersedes TOP 1-1-010 dated 12 April 1976.

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

ITEM	REQUIREMENT
High speed paved road	see TOP 1-1-011[1*]
Improved gravel road	
Secondary road	
Perryman cross-country course No. 1	
Perryman cross-country course No. 2	
Perryman cross-country course No. 3	
Churchville area courses	
Belgian block course	

2.2 Instrumentation.

DEVICE FOR MEASURING:	PERMISSIBLE ERROR OF MEASUREMENT
Profile (profilometer system - see para 4.2)	

3. MONITORING TEST COURSE SEVERITY BY COMMITTEE INSPECTION. For many years, test course severity has monitored by a special committee which judges conditions by riding over the courses in an M151 truck. The driver has attached to his/her chest an accelerometer which records how many times acceleration imparted to his/her torso exceeds 0.5, 1.0, and 2.0 g's.

Committee members are selected from experienced test directors or supervisors who are familiar with the test courses, their purposes and desired characteristics. Each committee member logs a rating of excessively severe, acceptable, or insufficiently severe for each definable section of a test course, along with his/her personal judgment of the cause of any changes that have occurred since the previous inspection.

Test course inspections are conducted by the committee on a monthly basis. More frequent inspections may be required, however, to correct the effects of climatic conditions and test usage. To obtain comparable data, the same committee inspects each course as in previous inspections using the same vehicle, if possible. The vehicle is maintained in the same condition as in previous inspections with particular attention given to its suspension system, shock absorbers, and tire inflation pressures. For a given course, the same driver is used for each inspection, if possible. If another driver must be used, he/she should have the same build, driving expertise, etc., as the regular driver.

For a given course, a vehicle with a different wheelbase will behave differently and will produce a different measurement. Vehicle speeds and accelerometer count control limits for each course are shown in Table 1. The time to traverse each course and length of each course are recorded for use in computing the average course speed. These data are plotted on the test course quality control chart (fig. 1)[2] to identify course severity with respect to established upper and lower control limits for each g-range count and previous inspections. In addition to

*Superscript numbers correspond to reference numbers in Appendix A.

the number of counts for each g range, the percentage of the total g-count distribution for each g range is shown. The quality control charts are used in conjunction with the committee's assessment of course conditions to determine the cause of significant changes in course severity and maintenance necessary to bring the severity level to within its control limits. In some cases, it may only be necessary to deepen or fill in certain potholes/ruts; in other cases, complete regrading may be required.

TABLE 1. TEST COURSE INSPECTION LIMITS

Course	Speed (mph)	Time to Traverse Course (sec)		Number of g Counts					
				Between 0.5 and 1.0		Between 1.0 and 2.0		Above 2.0	
		LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Improved Gravel Road	35	234	253	2	6	0	0	0	0
Secondary Road A (Perryman)	25	340	397	180	275	38	67	0	8
Perryman Cross-Country No. 1	25	786	861	415	605	80	165	12	28
Perryman Cross-Country No. 2	15	435	480	65	115	5	13	0	2
Perryman Cross-Country No. 3	15	833	945	385	505	60	90	2	10
Churchville Hilly Cross-Country Course B	*15/30	657	709	90	140	15	25	0	3
Churchville Hilly Secondary Road C	35	270	286	2	9	0	0	0	0
Belgian Block	**20/25	127	133	114	271	25	43	0	0

*Lower speed used for rougher portion of course
**Lower speed used for turns
LCL - Lower control limit
UCL - Upper control limit

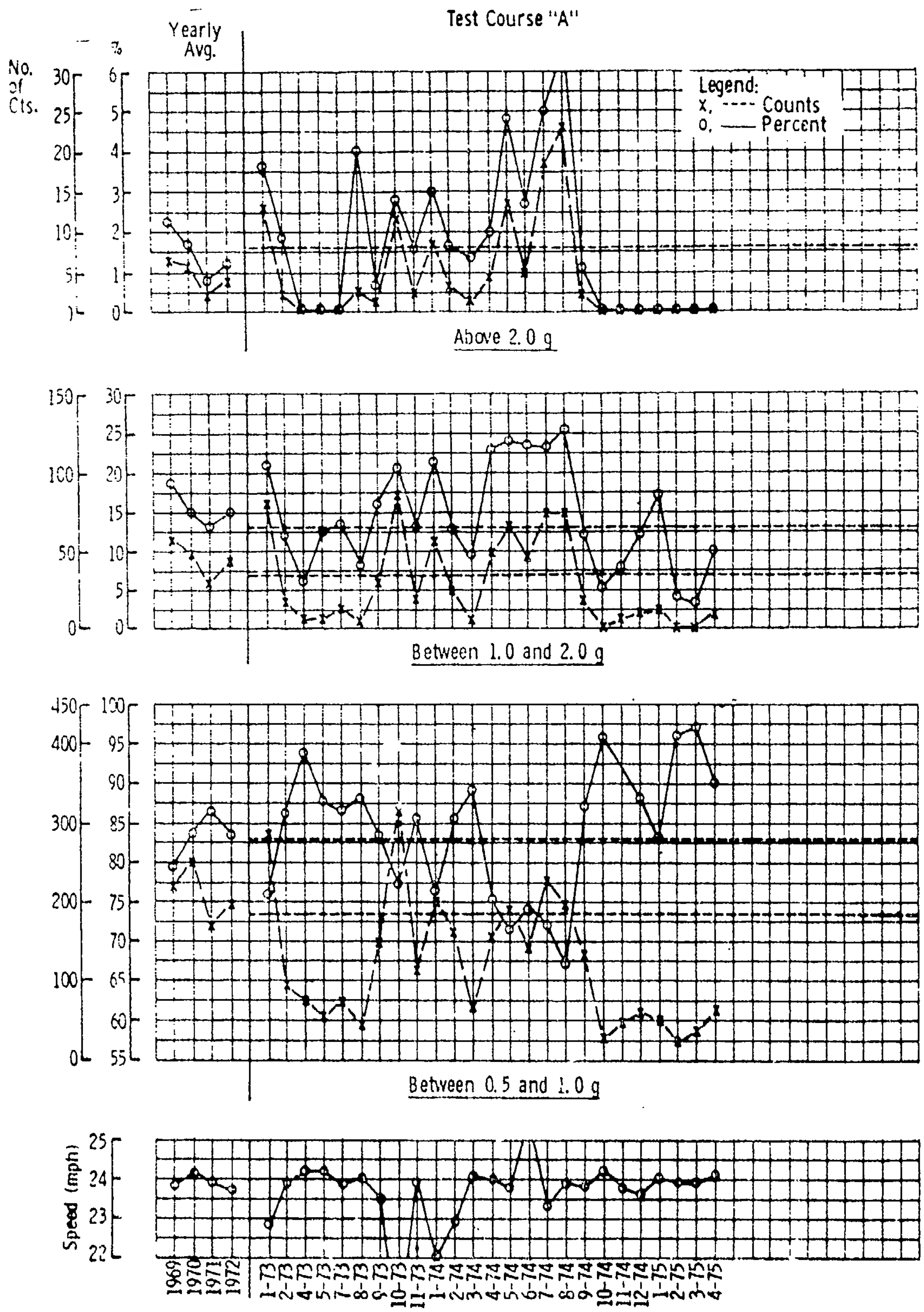

Figure 1. Typical test course quality control chart.

4. DETERMINING TEST COURSE SEVERITY BY MEASURING COURSE PROFILE. Test course severity can be determined quantitatively by analyzing the PSD of the course profile.[3] A road course profile can be represented by a nonperiodic wave composed of all harmonics of a fundamental frequency infinitesimally close to zero. The spectral density of such a wave is proportional to the square of the amplitude of the function and is continuous (not a line spectrum). Similarly, the energy absorbed by a vehicle in contact with the road is proportional to the square of the height of the terrain above an arbitrarily chosen zero level. The energy or power, expressed as a function of frequency, is the PSD of the terrain surface which is therefore directly related to the roughness of the road and to the energy absorbed by the vehicle. The relative roughness of any road can be determined by comparing the PSD of the road to the PSD of known or standard roads. This method is a direct measurement and is not influenced by vehicle transfer function, speed, or driver response.

Sufficient data have not yet been collected to establish a standard or control limits for the PSD curves of the courses covered in this TOP. When these data become available, they will be included.

4.1 Course Profile Geometry. A course profile can be represented by cartesian coordinates, with y depicting course height and x, the horizontal distance traveled. To measure these parameters, a small wheel frame is towed over the course. In Figure 2, the symbol θ_p is approximately equal to the angle of inclination of the curve, y = f(x). NOTE: If the base of the wheel frame is small (approaching 0), θ_p would equal the actual angle of inclination. Sin $\theta_p = \Delta y/\Delta s \approx dy/ds$ and cos $\theta_p = \Delta x/\Delta s \approx dx/ds$ in which s is the distance traveled along the curve.

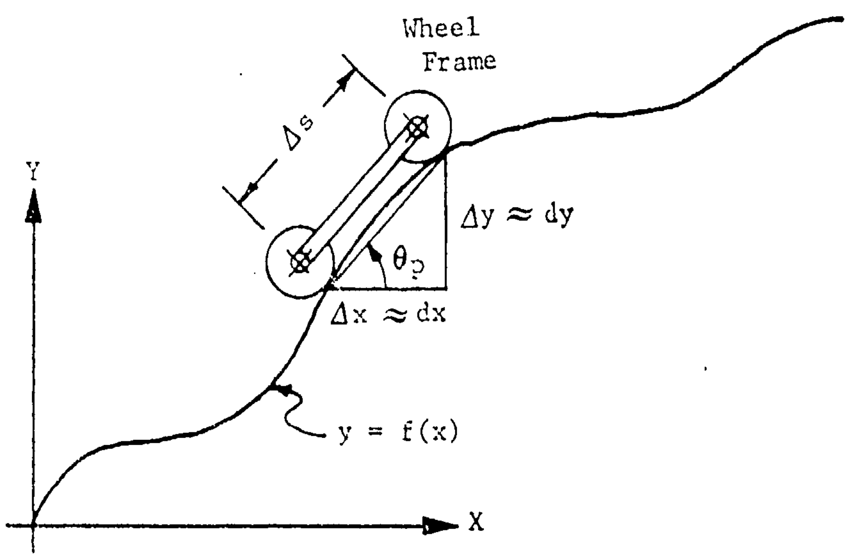

Figure 2. Course profile geometry.

The desired x,y parameters can now be obtained by integrating as follows:

$$\int \sin \theta_p ds = y \text{ (height)}$$

$$\int \cos \theta_p ds = x \text{ (distance)}$$

4.2 Profile-measuring Equipment. Test course profiles are measured with a profilometer system which consists of a tow arm, data-acquisition subsystem, and mobile mini-computer-based data analysis system. The profilometer tow arm (see fig. 3) obtains the slope of the test course and distance the wheel frame traverses the test course. The data are processed and stored by the microprocessor-based data-acquisition subsystem. Analog data are conditioned, filtered, and digitized. The microprocessor transforms digitized data points into instantaneous slope data and stores the solutions in bubble memory. These data are then transferred to the data analysis system for processing. This system produces PSD, amplitude distribution, and x-y coordinate plots of the terrain profile. Because the data are computer-based, a wide variety of analyses can be readily obtained.

A two-axis, vertical gyro with a potentiometer on the pitch axis is used to indicate the pitch angle (α) of the tow arm. The angle of the wheel frame relative to the tow arm (β) is indicated by a relative angle potentiometer. These angles added together form the angle of the terrain relative to the horizontal ($\alpha + \beta = \theta_p$). Horizontal orientation is indicated by 0 volts; positive angles are indicated by positive voltages, and negative angles by negative voltages.

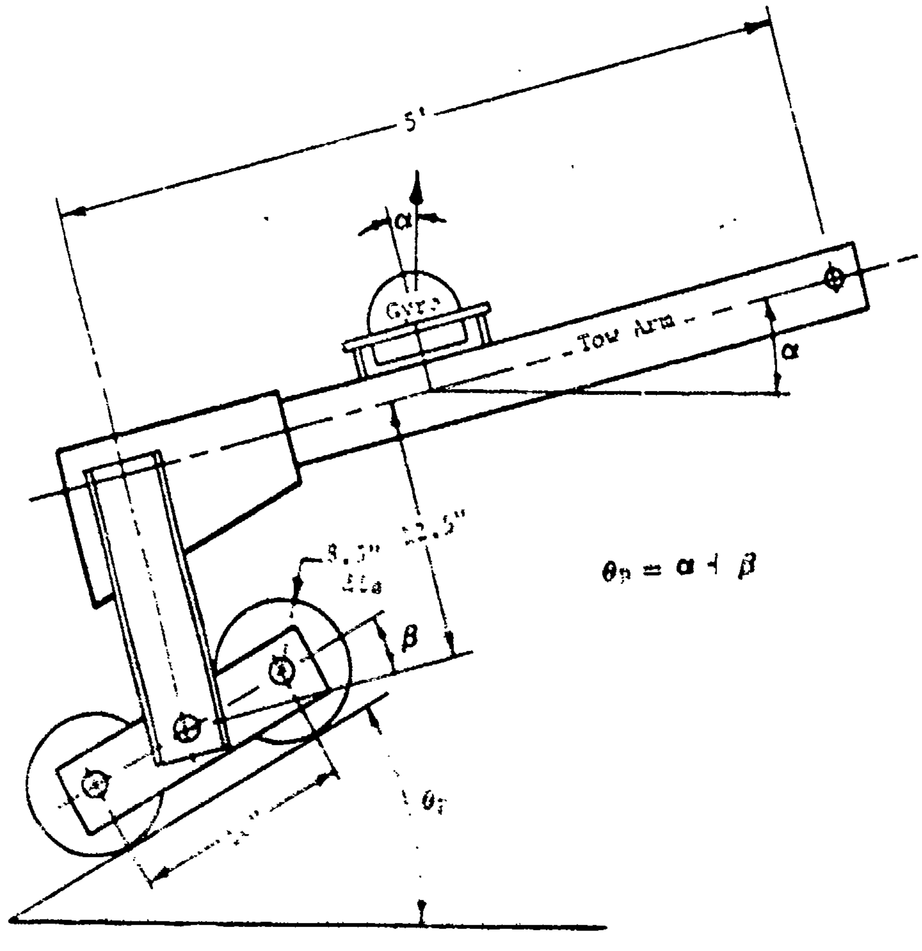

Figure 3. Profilometer tow arm geometry.

Four magnets mounted on the rear wheel and a pickup coil mounted on the wheel frame are used to measure distance. As each magnet passes the coil, a pulse is induced, thus providing data sampled at equal increments (currently 16.8 cm) along the course surfaces. A block diagram of the on-board digital data-acquisition system is shown in Figure 4.

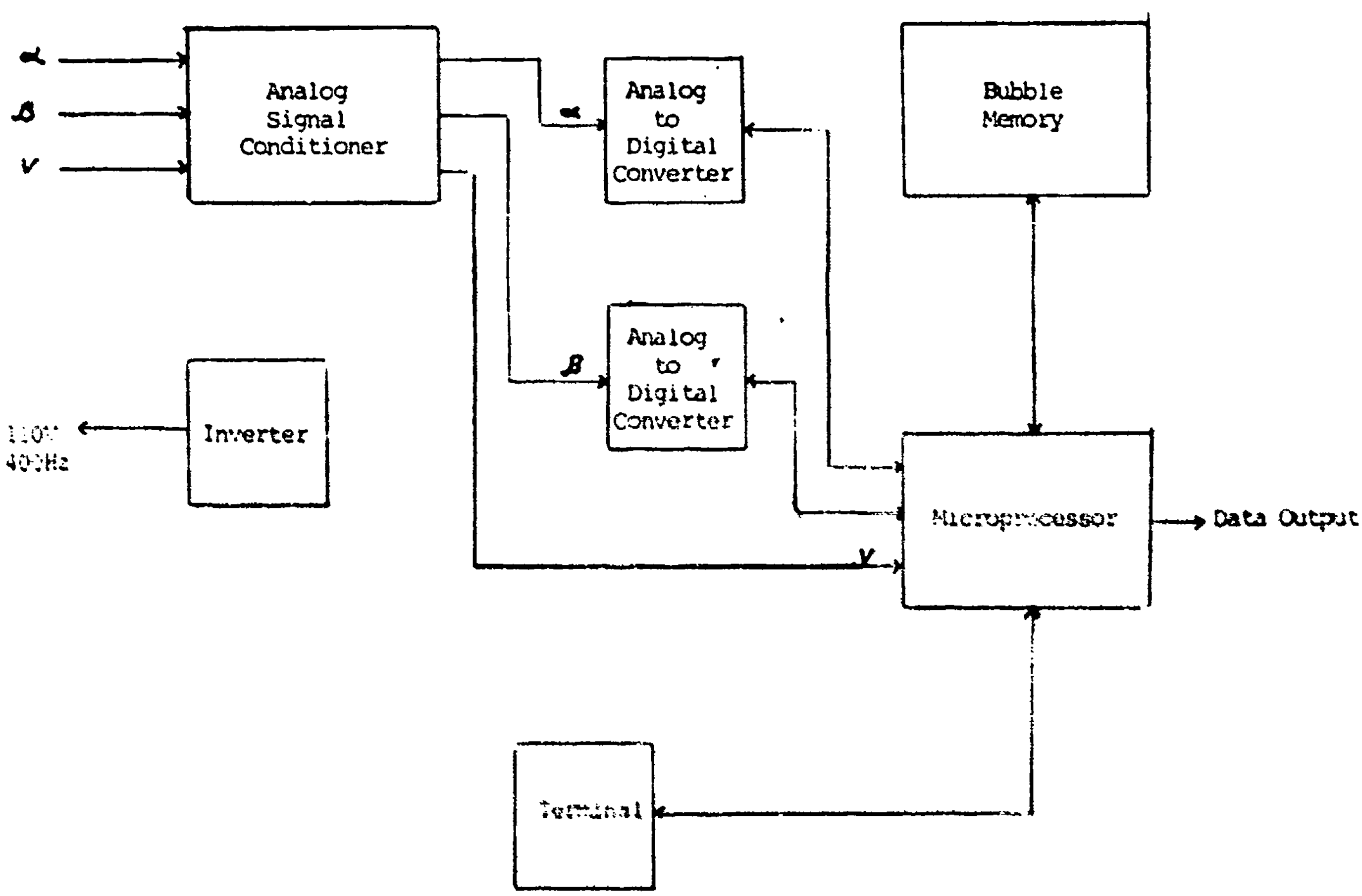

Figure 4. Data-acquisition system block diagram.

Figure 5 shows the profilometer mounted on a 1/4-ton truck, M151 series. Installation time is 15 to 30 minutes. Modified shock absorbers, pressurized to about 240 kPa (35 lb/in.^{2}), are used to maintain a continuous contact between the wheel and ground. This inflation gives the profilometer tires approximately the same bearing pressure as the truck tires. Towing speeds up to 16 km/hr (10 mph) can be attained. The important factor is to drive slowly enough to prevent the wheels of the profilometer from bouncing.

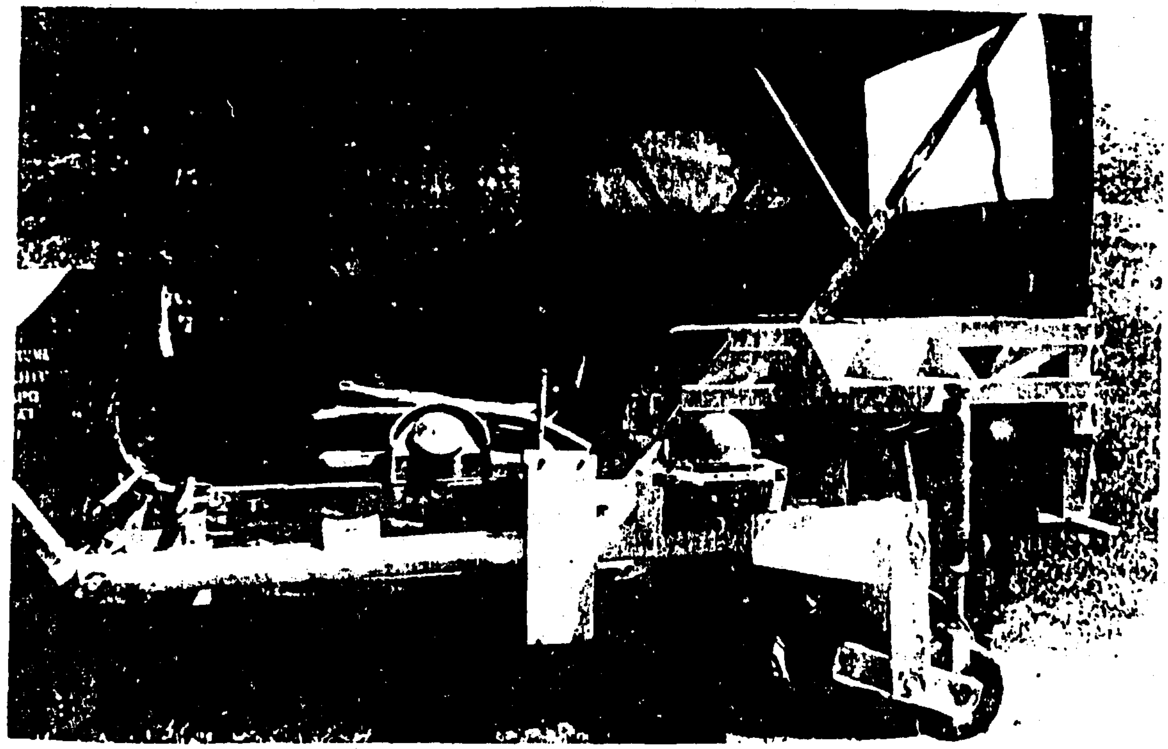

Figure 5. Profilometer mounted on a truck.

5. PSD ANALYSIS OF APG TEST COURSES. The various endurance test courses at APG were measured for their severity using the profilometer system. Before these measurements were made, the profilometer system was calibrated on a fixed course with known characteristics. A single pass of the vehicle along the center of each test course was made to obtain a characteristic PSD. This single pass is considered sufficient since the PSD curves of several passes across the width of a course have shown reproducibility to within 3 to 5 dB of each other (except for shoulder ruts). The courses measured and the resulting PSD curves are described in the following paragraphs in order of increasing severity. These curves were plotted in terms of power per unit spatial frequency versus spatial frequency. Hence, the units will be ft^2/cycle per ft = ft^3 for the ordinate and cycles per ft = ft^{-1} for the abscissa. These PSD's are general characterizations of the severity of each test course. Their actual severity at any given time varies as influenced by the environment, test course maintenance, and usage. The area under a PSD curve is related to the overall roughness of a profile. The slope of the PSD curve indicates the nature of the roughness. A steep slope indicates proportionately more low frequency content which should affect universal joints, transmissions, and other drive train components. A shallow slope, conversely, indicates proportionately more high frequency content which should affect wheel bearings, shock absorbers, and other suspension components.

5.1 High Speed Paved Road. This is a 5-km (3-mi) straightaway with banked turnaround loops at each end for tests requiring uninterrupted operations such as cooling tests, operation at high speed, etc. The pavement is continuous asphalt and the course is in the Perryman test area.

The PSD of this course (fig. 6) is the lowest obtained. The small peak at approximately 0.11 cycle/ft indicates some periodic disturbance with a period of 3 m (9 ft). This disturbance could result from a number of mended cracks that occur every 3 m, or low amplitude undulation in the course with a period of 3 m.

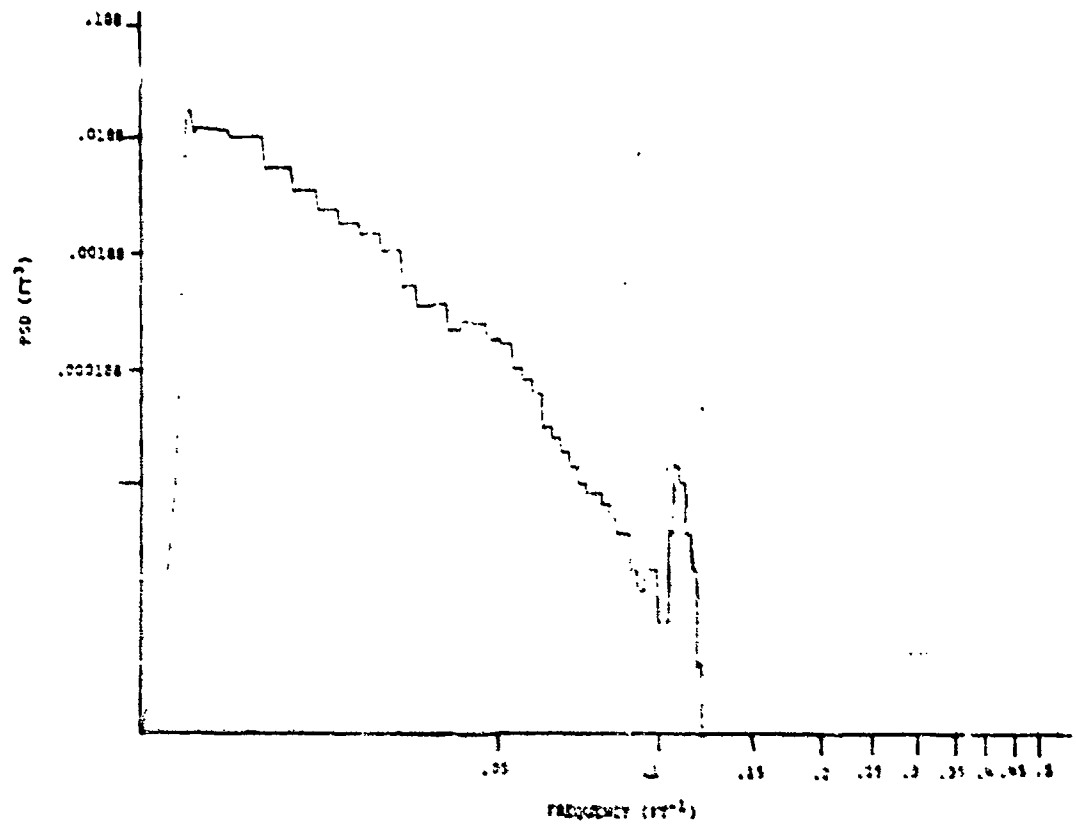

Figure 6. PSD of high speed paved road.

5.2 <u>Improved Gravel Road</u>. This road is in the Munson test area (see TOP 1-1-011) is a loop of about 3 km (2 mi) with left and right curves. The surface is compacted gravel and dirt, maintained by grading.

The PSD of this course (fig. 7) is higher than that of the high speed paved road, indicating higher overall roughness. The slope of the gravel road PSD is also more shallow, indicating proportionately more high frequency content.

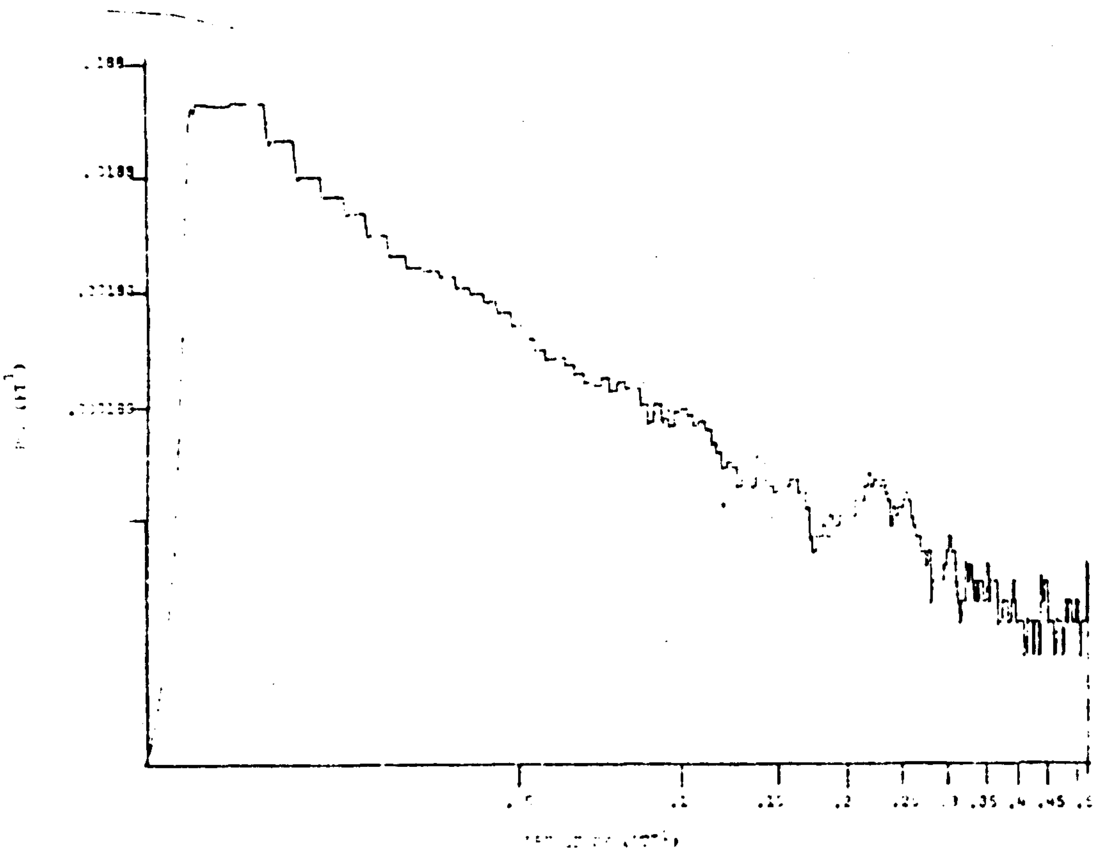

Figure 7. PSD of improved gravel road.

5.3 Secondary Road. A 3.8-km (2.4-mi) secondary road in the Perryman area is used for tests of various types of vehicles. This road has sharp and sweeping turns typical of unimproved country roads. The course is maintained by grading and filling with bank gravel and crushed stones as necessary.

The PSD of this course (fig. 8) is higher than that of the gravel road, indicating more overall roughness. The slopes of both curves are the same, indicating the same proportion of frequency content. In the area between 0.12 and 0.35 cycle/ft, a deviation from the straight line fit occurs.

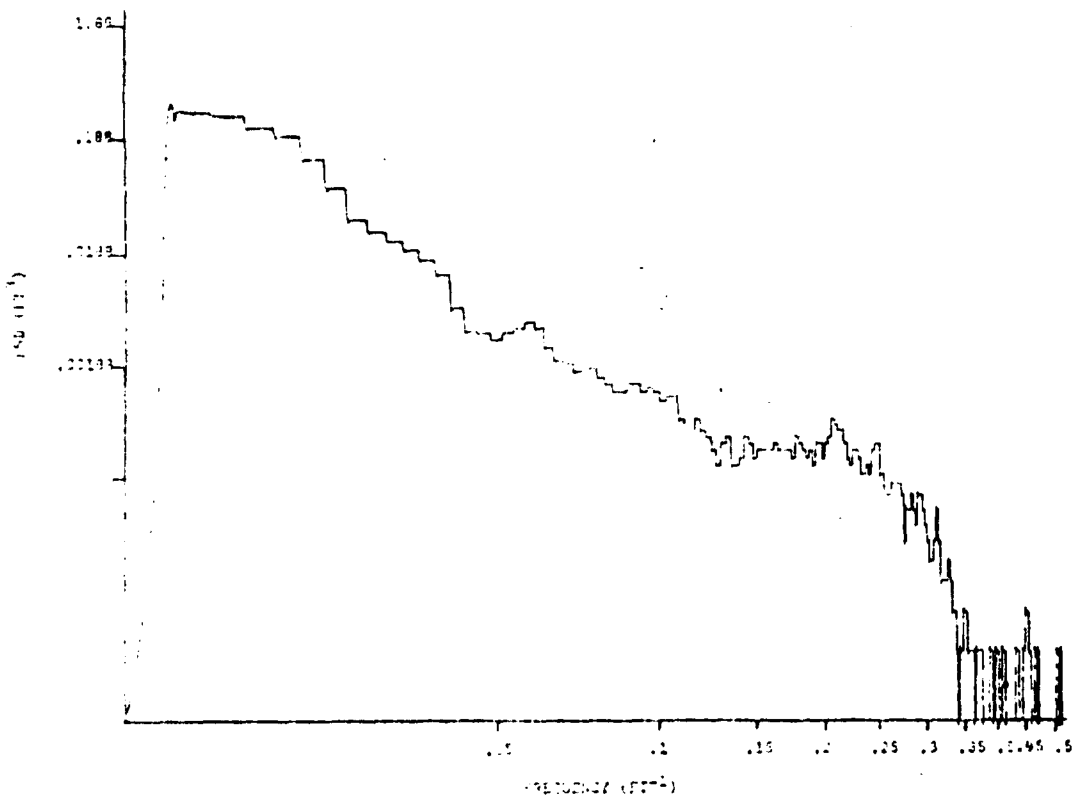

Figure 8. PSD of secondary road.

5.4 Perryman Cross-country Course No. 1. This is a moderate course with a substantial roadbed primarily of quarry spall and bank gravel. The loop indicates both sharp sweeping curves, and the surface ranges from smooth to rough; roughness is due to potholes, washboard, and rutting. Potholes and other sharp depressions are normally limited to 15 cm (6 in.) deep by filling with crushed stone. During wet weather, the course as a whole is characterized by light mud which affects wheeled vehicles, mainly by splash.

The PSD of this course is shown in Figure 9. This curve has the same slope as secondary road A and a similar bulge in the area between 0.15 and 0.3 cycle/ft. The PSD of this course is slightly higher than that of secondary road A.

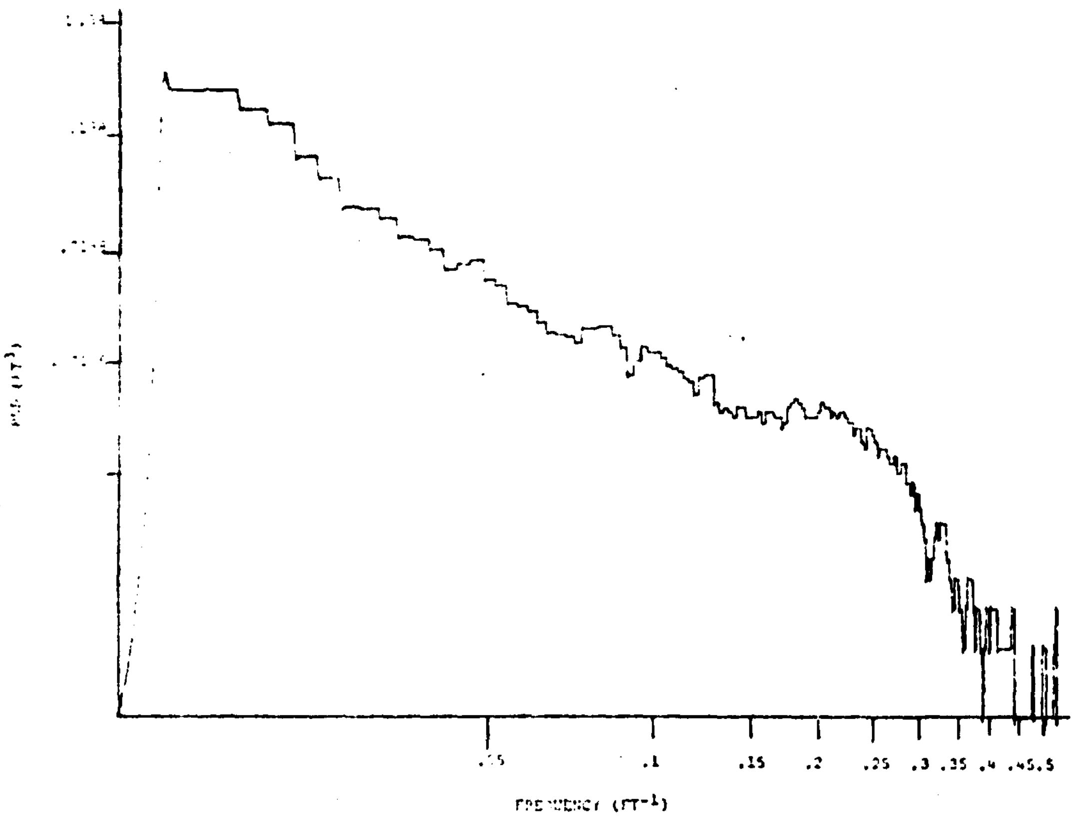

Figure 9. PSD of Perryman cross-country course No. 1.

5.5 Perryman Cross-country Course No. 2. This course is laid out in a loop of moderately irregular terrain. The native soil includes sassafras loam, a silty loam with 17.3% clay content, and sassafras silt loam with less than 15% clay. Surfaces range from smooth to rough, and there are sweeping turns. Under wet conditions, severe mud is present; when dry, the course is extremely dusty. Potholes and depressions are limited to 46 cm (18 in.) deep.

The PSD of this course (see fig. 10) is higher than that of course No. 1. The slope is steeper than that of course No. 1. This indicates that course No. 2 has more overall roughness and proportionately more low frequency content than course No. 1. There is very little deviation from the straight line trend.

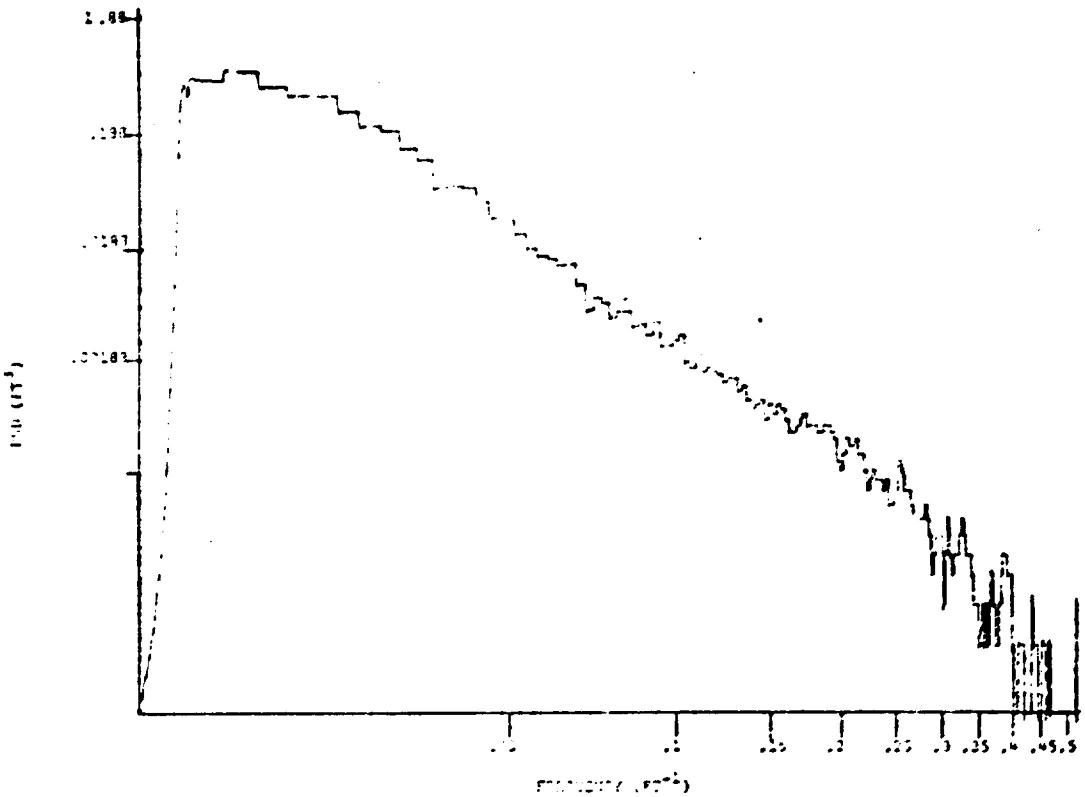

Figure 10. PSD of Perryman cross-country course No. 2.

5.6 Perryman Cross-country Course No. 3. This is a rough course of native soil similar to the soil of course No. 2. Mud ranges from light (with free water) to cohesive. Although dust is severe when the course is dry, there is always mud in some areas. Much of the course is rough due to many years of test operations of tracked vehicles. Potholes and depressions are limited to 90 cm (36 in.) deep.

The PSD of course No. 3, shown in Figure 11, is higher than any other and has the steepest slope encountered. The PSD also indicates that course No. 3 has proportionately more low frequency content and overall roughness than course No. 2.

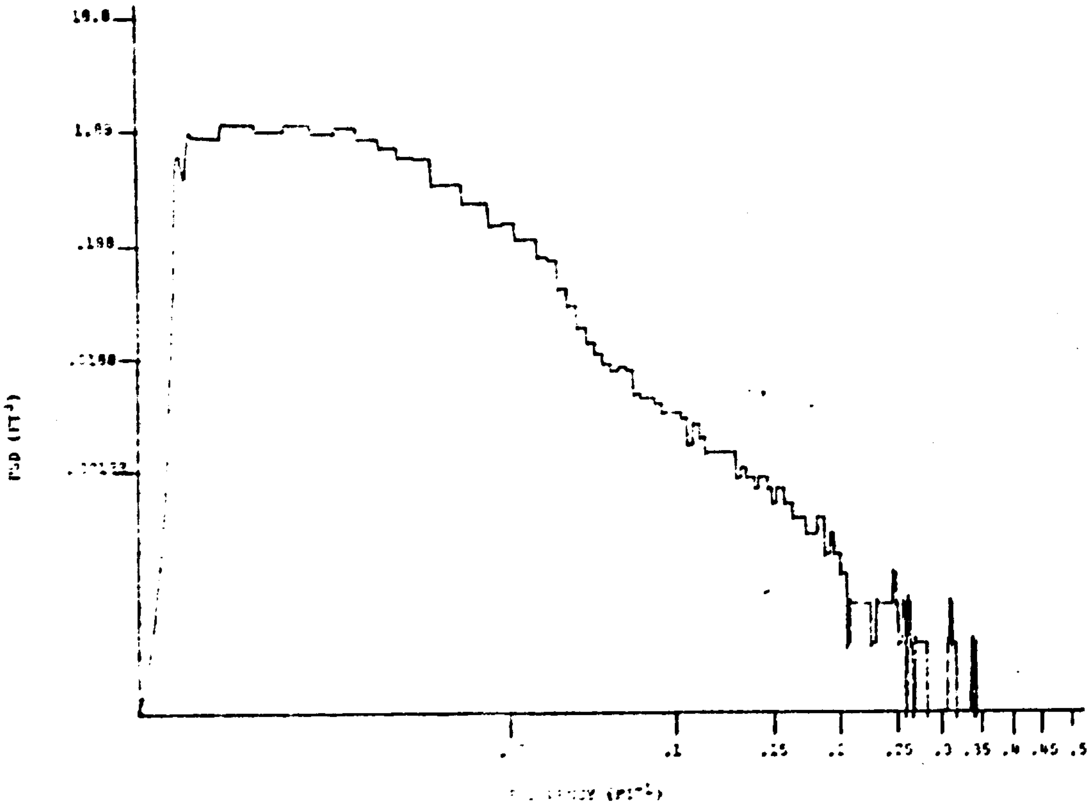

Figure 11. PSD of Perryman Cross-country course No. 3.

5.7 Churchville Area Courses. These courses are characterized by a series of steep hills with slopes up to 30%. The range of the profilometer analog retrieval system is limited to ±254 cm (±100 in.) to afford good resolution of microprofile. This range is considerably less than the height of the hills in Churchville. Because these hills are steep and spaced closely, it is impossible to filter out these terrain changes without filtering out low frequency portions of the microprofile. Although the total PSD plots are shown (see fig. 12 through 14), only the portions above 0.1 cycle/ft should be examined.

Figures 12 and 13 are PSD plots of Churchville course B which consists of grades up to 27%. The terrain is moderate to rough native soil and stone ranging from muddy to dusty, depending on the weather. The first half of course B is significantly more severe than the second half. The PSD of the first half is about the same as that of Perryman cross-country course No. 2 above the cutoff frequency of 0.1 cycle/ft. The PSD of the second half of course B falls between that of secondary road A and the improved gravel road.

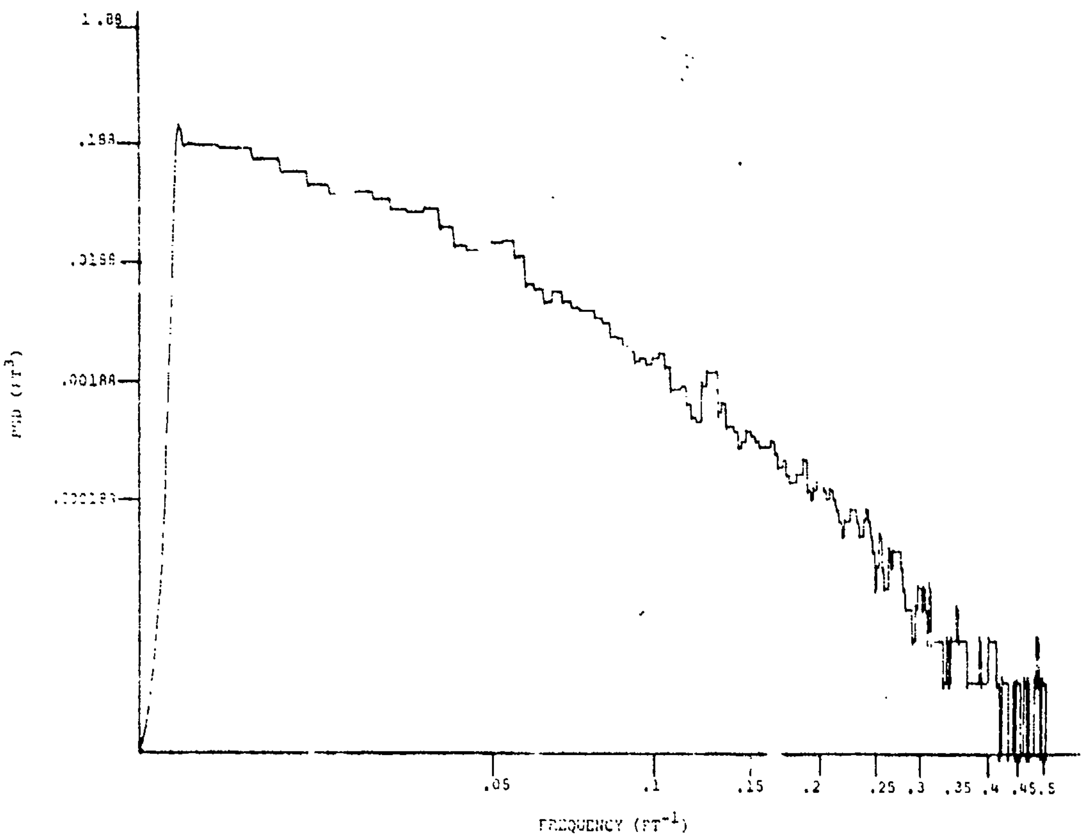

Figure 12. PSD of Churchville course B, first half.

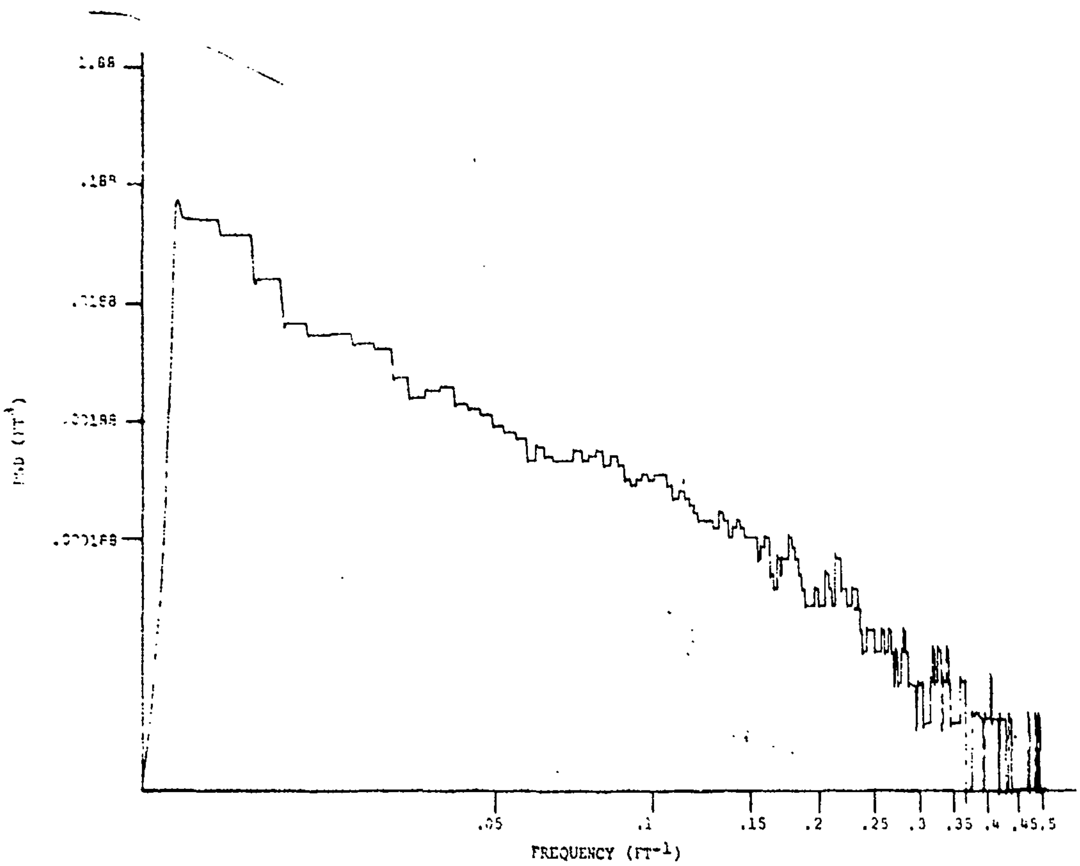

Figure 13. PSD of Churchville course B, second half.

Figure 14 is a PSD plot of Churchville course C which is a 2.4-km (1-1/2-mi) secondary road test course with controlling grades of 10% and turnarounds at each end. This PSD is about the same as that of the improved gravel road above the cutoff frequency of 0.1 cycle/ft.

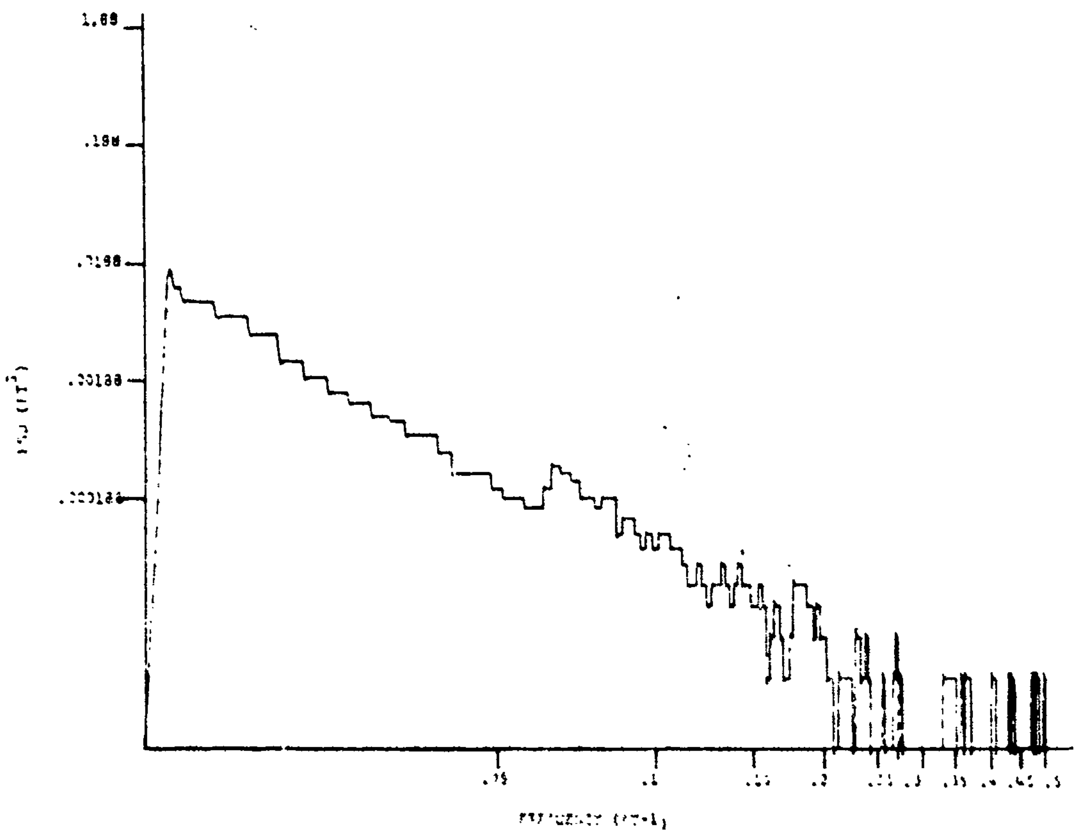

Figure 14. PSD of Churchville course C.

5.8 <u>Belgian Block Course</u>. This is a paved course with unevenly laid granite blocks forming an undulating surface. It duplicates a rough cobblestone road such as is found in many parts of the world. About 1.2 km (3/4 mi) long, the course is useful as a standard rough road for accelerated tests of wheeled vehicles. It is generally included in cycles of courses used for vibration studies. The motion imparted to a vehicle is a random combination of roll and pitch and high frequency vibrations.

The PSD of the Belgian block course, shown in Figure 15, has the most shallow slope of all the courses examined. This indicates that a large proportion of the energy is high frequency. The peak at 0.1 cycle/ft indicates periodic undulation at this frequency.

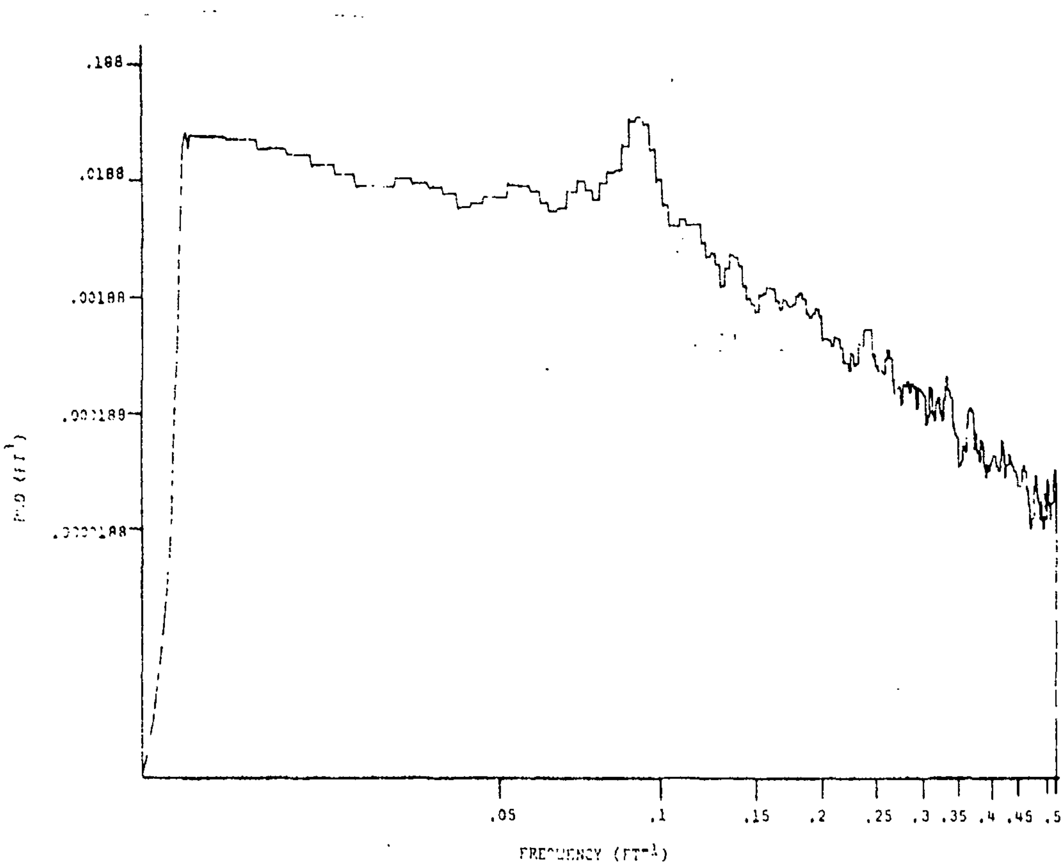

Figure 15. PSD of the Belgian block course.

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APPENDIX A

REQUIRED REFERENCES

1. TOP 1-1-011, Vehicle Test Facilities at Aberdeen Proving Ground, 6 July 1981.

2. APG Report No. APG-MT-4105, "Special Study of Establishment of Quality Control Charts for Test Course Inspection Roughness", TECOM Project No. 9-CO-011-000-055, John P. Sobczyk, July 1972.

3. APG Report No. APG-MT-4533, "Special Study of Technique and Study of Automotive Test Course Index, Phase III", TECOM Project No. 9-CO-081-000-007, W. Scott Walton, October 1974.