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FRA/ORD-84/09

VALIDATION OF TRACK GEOMETRY INPUT TO THE VIBRATION TEST UNIT (VTU) AND ENDURANCE CAPABILITY OF THE VTU

JUNE 1984

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16. Abstract

This report describes a series of tests conducted at the Transportation Test Center, Pueblo, Colorado, to validate two forms of track geometry inputs to the Vibration Test Unit (VTU) in the Rail Dynamics Laboratory, capable of reproducing actual revenue track conditions. The first form consisted of reformatted Plasser geometry input produced by converting the Plasser mid-chord offset data into a Space Curve format with a special software. The second track geometry input was developed based on the Locomotive Track Hazard Detector (LTHD) concept, and was produced by processing the time histories of special axle-mounted accelerometers into a space curve format. The results indicated that the responses of the test vehicle on the VTU, excited with the LTHD input, compared closely with the corresponding responses monitored on the actual track, while the reformatted Plasser input showed considerable variation in the vehicle response on the VTU at speeds of 30 mph and above - in both amplitude levels and frequency content.

After the identification of a suitable form of input to the VTU which closely duplicated actual track conditions, a series of endurance cycle test runs was performed to demonstrate the capability of the VTU to operate for sustained periods of time using the track geometry as the input excitation.

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ACRONYMS

AL	Alignment
DRS	Data Reduction System
FAST	Facility for Accelerated Service Testing
FFT	FAST Fourier Transform
ICSN	Integrated Computer System Network
LP	Left Profile
LTHD	Locomotive Track Hazard Detector
PGS	Profile Generation System
PMB	Project Management Building
PSD	Power Spectral Density
PTT	Precision Test Track
RDL	Rail Dynamics Laboratory
RP	Right Profile
RTT	Railroad Test Track
SFD	Second Finite Difference
TDT	Train Dynamics Track
TTC	Transportation Test Center
UDB	User Data Base
VTU	Vibration Test Unit

ABBREVIATIONS AND METRIC EQUIVALENTS

°	degrees	
', ft	foot	= .03048 m
g	unit of acceleration relative to gravity	
Hz	Hertz	
", in	inch	= 25.4 mm
kips	kilopounds	= 453.59 kg
lb	pound	= 453.59 grams
mph	miles per hour	= 1.6094 km/h
%	percent	
rms	root-mean-square	
sec	second	
	ton (avoirdupois)	= 0.907 metric tons

EXECUTIVE SUMMARY

The Vibration Test Unit (VTU) in the Rail Dynamics Laboratory at Pueblo, Colorado, can be used for vibration testing of railroad vehicles with revenue track input. Until recently the usual source of track geometry input to the VTU consisted of Plasser car digital tape recordings of track displacements as a function of distance along the track. In previous attempts to use track geometry inputs, certain problems were encountered with the mid-chord measuring technique used in the Plasser car track recordings when converted as input to the VTU. Special software was developed by the MITRE Corporation, which attempted to alleviate the source of the limitations associated with the above measuring technique. The MITRE software was used to convert the mid-chord offset data into a Space Curve Format, which was used as the reformatted Plasser geometry input to the VTU.

A second track geometry input to the VTU was developed based on the Locomotive Track Hazard Detector (LTHD) concept, which produced displacement history data obtained by processing the time histories of special axle-mounted accelerometers. Tests were conducted at the Transportation Test Center, Pueblo, Colorado, to validate a suitable form of input to the VTU which closely duplicated the actual revenue track input. The results indicated that the responses of the test vehicle on the VTU, excited with input based on LTHD concept, compared closely with the corresponding responses monitored on the actual track, while the reformatted Plasser time history input to the VTU produced responses which showed considerable variation in both amplitude levels and frequency content at simulated speeds of 30 mph and above. The close agreement between the responses during the track tests and VTU runs with the LTHD time history input has opened up new realms of testing capabilities for the VTU, such as analysis of component fatigue, vehicle natural frequencies, ride comfort, suspension characteristics and lading damage evaluation on a given revenue track. After the identification of a suitable form of input to the VTU which closely duplicated actual track conditions, a series of endurance cycle test runs was performed to demonstrate the capability of the VTU to operate for sustained periods of time using track geometry as the input excitation. The endurance cycle was designed to simulate in-service and yard conditions experienced by a freight car, with three hour continuous excitation of the test vehicle on the VTU, followed by an impact test of the vehicle at different speeds on the actual track.

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VALIDATION OF TRACK GEOMETRY INPUT TO THE VIBRATION TEST UNIT (VTU) AND THE ENDURANCE CAPABILITY OF THE VTU

INTRODUCTION

The VTU is used by researchers in studies of suspension characteristics of rail vehicles, component and vehicle natural frequencies, ride comfort, lading responses, component fatigue, and rock and roll tendencies. A stationary rail vehicle equipped with two trucks is subjected to controlled vertical and lateral vibration inputs at the wheels, creating dynamic effects of a revenue track on the vehicle. The VTU consists of twelve servo-controlled hydraulic actuators, eight vertical actuators (one under each of the eight wheels of a mounted test vehicle), and four lateral actuators in line with the four axles (Figure 1). The computer network consists of two Varian V-73 mini-computers, one used for profile generation to drive the VTU, and the second for acquisition and recording of test data from the VTU. The profile generator provides the VTU with three distinct types of vibration profiles: Mathematically formatted periodic inputs, random inputs through a function generator and time history inputs. The first form of input currently contains sinusoidal, rectified sine, haversine and exponential wave forms. The time history wave forms are obtained from the digital tape recordings of actual track geometry consisting of left and right vertical rail profiles and lateral alignment measurements. The signal generation computer can play back the track geometry tape over a wide range of speeds to drive the hydraulic actuators such that the VTU can replicate the conditions a test vehicle would experience in actual service. The validation of two types of track geometry input to the VTU are

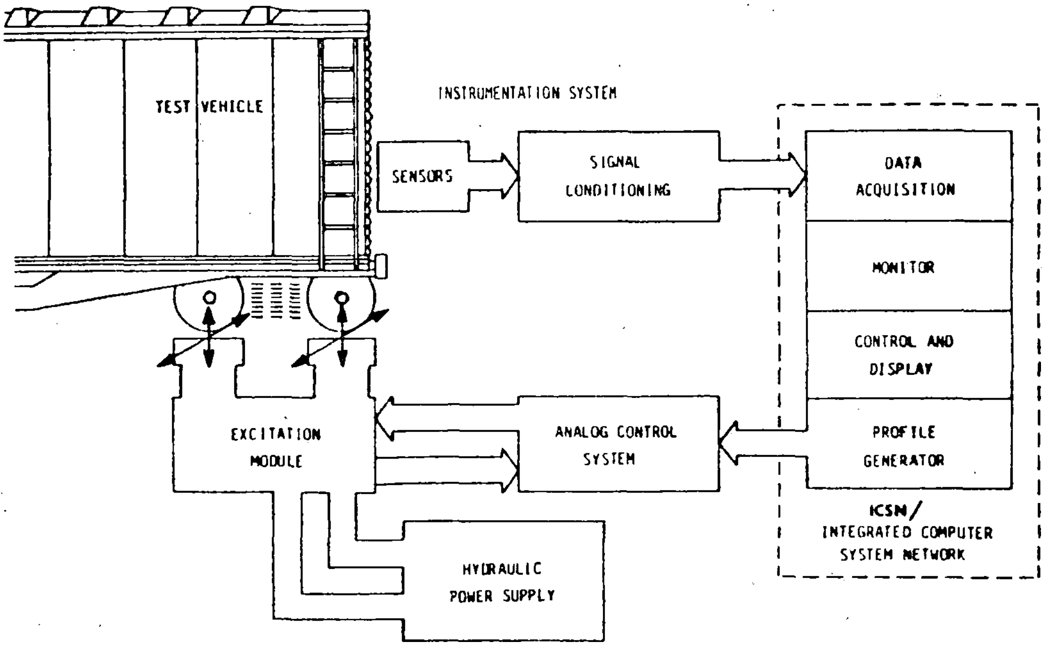

FIGURE 1. SCHEMATICS OF THE VIBRATION TEST UNIT (VTU).

described in this report, focusing on their applicability to produce the same responses of the car on the VTU as observed on the actual track.

PLASSER CAR TRACK GEOMETRY MEASUREMENT AND ITS PRESENT LIMITATIONS AS VTU INPUT

The Plasser track geometry car measures several parameters related to track irregularities such as variations in profile, alignment, gauge, cross level, superelevation, etc., for every foot of the track measured, and this information is generally used for track maintenance and related activities. The mid-chord offset measurement (Ref. 1) is commonly used to measure vertical (profile) and horizontal (alignment) deviations from a straight line joining two points on the rail, and this information is stored on tape, usually known as the Plasser car raw data tape, and then subsequently converted for use by the VTU. The mid-chord measuring technique has certain limitations (Ref. 2) in providing the correct vertical and lateral measurements of track. The Plasser Car measures the profile over a 31 foot chord between the front/rear measuring axle and the middle measuring axle (which is then calculated to a 62 foot base). There are two problems encountered in the measurement of a profile with mid-chord offset data generated by the Plasser Car. The first discrepancy in the profile measurement is explained in Figure 2. The figure shows a single irregularity in the rail and the resulting variation in the mid-chord offsets as the measuring beam passes from position A through B to C. It can be seen that the shape of the profile trace does not look very much like the actual shape of the rail.

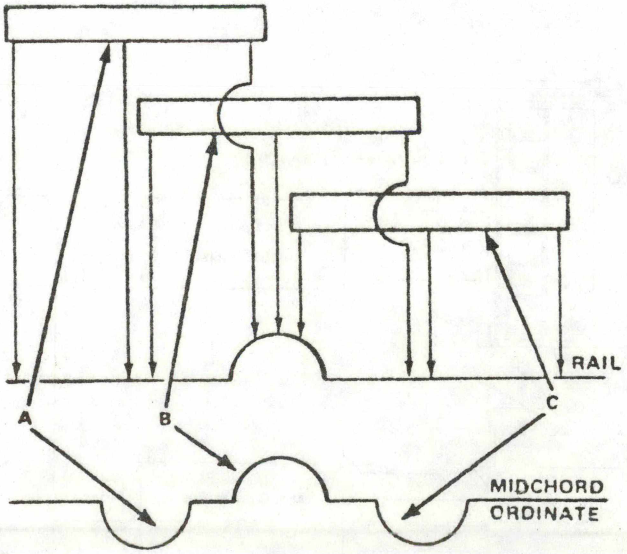

FIGURE 2. RAIL IRREGULARITY AND MID-CHORD ORDINATE REPRESENTATION.

A simple kink in the rail is transformed into three kinks on the recorded profile by the mid-chord offset system.

The second problem encountered with mid-chord offset data is one of frequency response as shown in Figure 3. If the Plasser Car encounters irregularities of the same wave length (or odd integral fractions of chord length) the measured response amplitude is doubled. If the wave length is an even integral fraction of chord length, the measured response amplitude is zero.

The MITRE Corporation attempted to correct the above discrepancies in special software, developed to convert this data into a space curve format. However, this method encountered certain problems resulting in "noise" associated with space curves, which in turn affected the response of the VTU.

It should be noted that MITRE Corporation has suggested measures which could be taken to improve the reformatted space curves. However, these corrective measures have not yet been evaluated.

The reformatted primary tapes are processed by the VTU control software, resulting in an amplitude time history tape containing twelve track displacements for the four axles of the test vehicle as a function of time. This tape is used as VTU input.

LTHD CONCEPT FOR TRACK GEOMETRY MEASUREMENT AND ITS APPLICATION AS VTU INPUT

The second track geometry input to the VTU originated as an offshoot of the Locomotive Track Hazard Detector (LTHD) development program,* which was conducted by the MITRE Corporation, under a contract from the Federal Railroad Administration. This system provided a track geometry measurement capability that could be used by the railroads to detect unsafe track conditions during routine revenue operations (Ref. 3). The results of MITRE's LTHD computer analysis and field testing showed that this concept could be used for providing a simple and effective method of acquiring data for track geometry measurement purposes which included track profile, cross level and alignment. This measurement system (referred to as the LTHD system in the present context) essentially consists of two vertical accelerometers, one mounted on each end of a truck axle, and one lateral accelerometer mounted at either end of the same axle. The car being tested on the VTU should be equivalent to the car used to collect data on any given revenue track. Figure 4 shows the LTHD sensor configuration and the locations of three axle-mounted accelerometers for acquisition of data on a given track. In this concept, the accelerometer data are filtered and digitized at one foot intervals. The analog filtered acceleration data are converted into displacement data. This is accomplished using a modified Second Finite Difference (SFD) operation. Figure 5 presents the general principle of converting LP, RP and AL (left profile, right profile and alignment) accelerometer data to space curves through the SFD operation and double integration process. A special software system based on the above principle converts the time histories of the LTHD accelerometers (acquired on a given track) into displacement histories with respect to spatial coordinates which contain space curves of left profile, right profile, cross level, lateral truck displacement, and superelevations. These reformatted primary tapes are reprocessed by the available VTU software package into amplitude time history tapes which are used as the VTU input.

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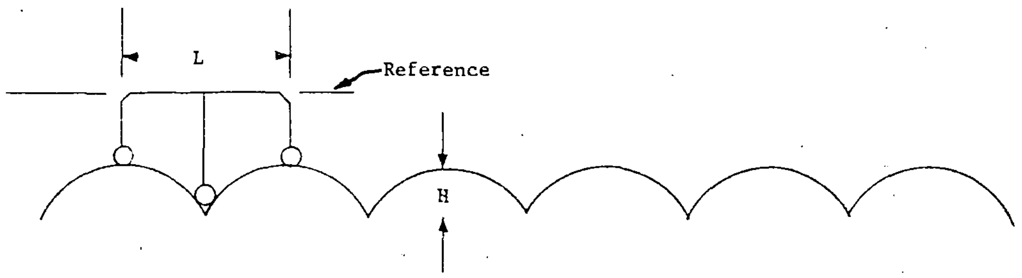
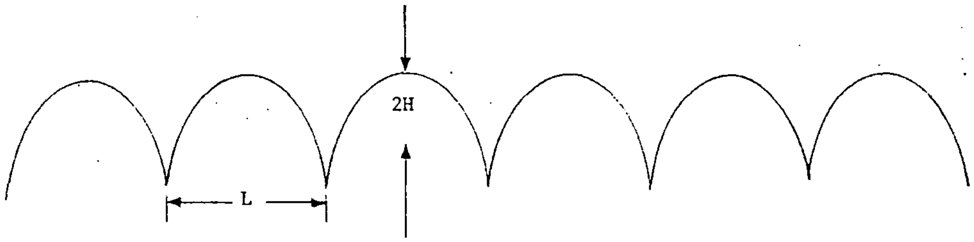
* A simple measurement system mounted on a locomotive that can be used to detect potentially unsafe track condition.



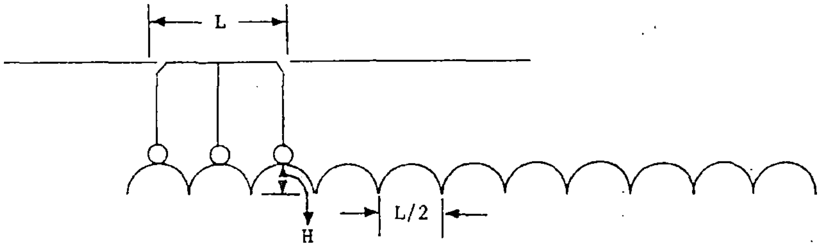
Actual Profile of Wavelength L and Amplitude H.

⇩ Mid-Chord Offset Measurement



Measured Profile of Double Amplitude 2H and Wavelength L.

(The above can also be shown to apply for odd integral fractions of wave lengths; i.e., 1/3 L, 1/5 L, 1/7 L, etc.)



Actual Profile with Wave Length L/2 and Amplitude H.

⇩ Mid-Chord Offset Measurement

Measured Profile of Zero Amplitude.

(The above can be shown to also apply where wave length = 1/4 L, 1/6 L, 1/8 L, etc.; i.e., even integral fractions)

FIGURE 3. FREQUENCY RESPONSE PROBLEM WITH MID-CHORD OFFSET PRINCIPLE.

AL = Lateral Accelerometer (Alignment)
LP = Left Vertical Accelerometer (left Profile)
RP = Right Vertical Accelerometer (Right Profile)

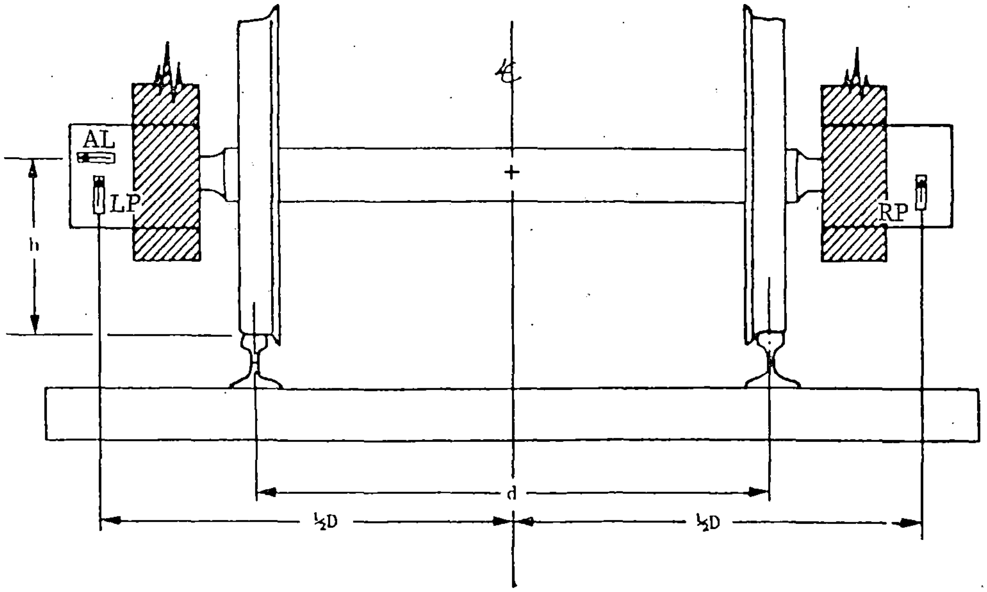
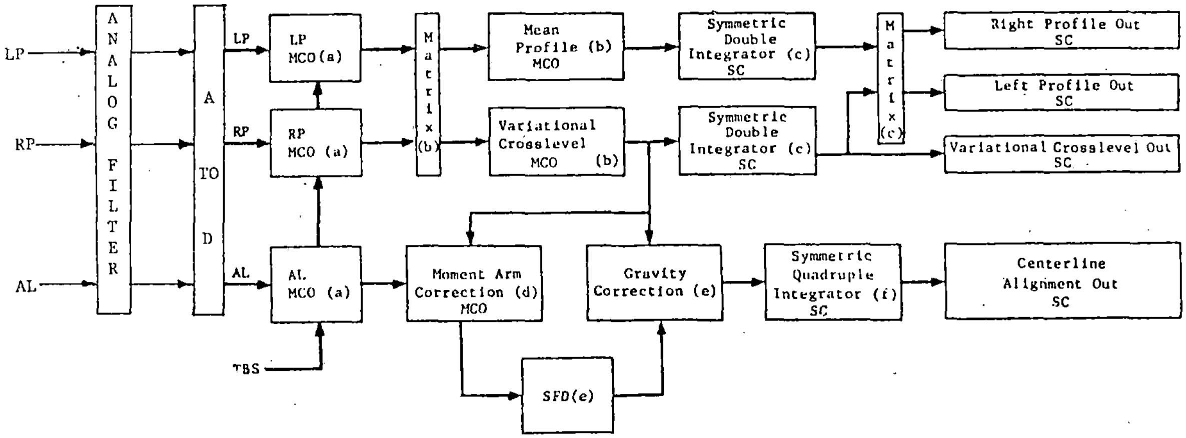


FIGURE 4. CONFIGURATION OF AXLE-MOUNTED LTHD ACCELEROMETERS.



MCO = Mid-chord Offset
LP = Left Profile (Left Vertical Accelerometer)
RP = Right Profile (Right Vertical Accelerometer)
AL = Alignment (lateral Accelerometer)
SC = Space Curve

FIGURE 5. LTHD TRACK GEOMETRY PROCESSING.

TEST OBJECTIVES AND METHODOLOGY OF TRACK GEOMETRY INPUT VALIDATION

The tests conducted at the TTC were developed to validate the two forms of track geometry input to the VTU (viz., LTHD and Plasser space curves) by comparing the responses of the test vehicle on the VTU with the responses of the same vehicle on the actual track.

The responses of the test car on the Precision Test Track at the TTC were acquired by recording data from the instrumented carbody lading and suspension systems which included axle-mounted LTHD accelerometers. The data from LTHD accelerometers was converted into amplitude time history tapes for the VTU to be used as LTHD track geometry input for validation. The Plasser car (EM-80) was run on the test track prior to LTHD track testing and the raw data was processed into Plasser time history tapes as the second VTU input for validation. The instrumented test car was placed on the VTU and subjected to input excitation prescribed by the above two forms of inputs. The responses of the test car on the VTU with both forms of inputs were compared independently with the actual responses during track tests. The responses of the selected accelerometers on the carbody and lading, as well as LTHD accelerometers, were compared in terms of frequency content and Power Spectral Density (PSD) amplitude levels.

The test vehicle was a 70-ton boxcar (50 ft 6 in length, 5277 cubic ft capacity) and the lading consisted of canned dog food in the stretch wrap configuration. Figure 6 presents the instrumented car with the following additional details.

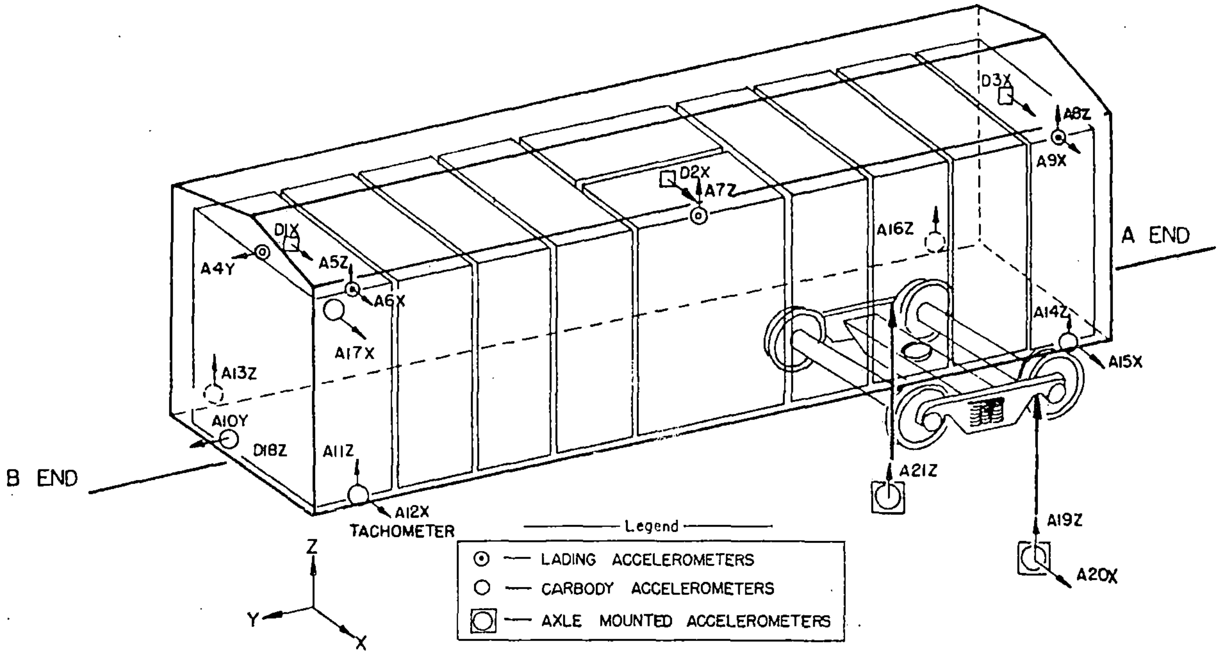


FIGURE 6. INSTRUMENTATION OF THE TEST VEHICLE (70-TON BOXCAR).

1. LTHD accelerometers were mounted on the leading axle of the leading truck. These accelerometers were enclosed in a foam chamber to isolate them from high frequency mechanical vibrations. One of the sensor packages contained both vertical and lateral accelerometers, while the other contained only a vertical accelerometer.

2. Accelerometers (1 volt/g) to measure accelerations in longitudinal, lateral, and vertical directions, and a roll rate gyro (60°/sec) were installed on the carbody.

3. Accelerometers (1 volt/g) to measure accelerations in all three directions were installed on the lading.

4. Lateral lading displacements were measured by Celesco stringpots.

5. A speed tachometer was installed on the trailing axle set during track test runs.

Table 1 presents the comprehensive description of instrumentation for the test vehicle.

The Precision Test Track on which track testing was carried out has a tangent section with known vertical perturbations. The tests were carried out on staggered, perturbed sections (roll mode) as well as on parallel perturbed sections (bounce mode) of 39 foot joints. The response of the LTHD accelerometers, carbody, and lading in both the "roll" and "bounce" modes was considered to be a good representation of vehicle response on a typical revenue track and, in turn, made the comparison of vehicle response on the VTU and on the PTT during validation tests more meaningful.

The track geometry data was acquired on the test track by the Plasser track geometry vehicle (EM-80), which is a self-contained, powered and instrumented car. It was operated on the test track at its normal data collection speed of 10 mph. The track geometry data was processed using the MITRE special software and formatted into proper profile generating system format as Plasser track geometry input to VTU.

The instrumented test vehicle was run on the Precision Test Track at speeds varying from 10 mph to 50 mph, and the acquired LTHD accelerometer data was processed using the MITRE special software and reformatted as LTHD track geometry input to VTU. For track testing, the test consist was made up of a locomotive leading a buffer car, followed by the instrumented test vehicle and the instrumentation car. The instrumentation car housed special filters and signal conditioners for the LTHD accelerometers and a source of on-board power for the complete instrumentation setup. The acquired data from different measuring instruments during track testing was processed through signal conditioners and filters. The processed data was digitized through encoders and transmitted via a telemetry transmitter installed in the instrumentation car. The transmitted signals were received by a telemetry receiver at the Project Management Building (PMB) of the TTC. After the received signals were decoded, the data was recorded on a digital magnetic tape by a PDP 11/34 digital computer. Digital to analog (D/A) conversion was performed for twelve (12) channels of recorded data and displayed on strip charts. Figure 7 outlines the track data acquisition schematics.

TABLE 1
DESCRIPTION OF INSTRUMENTATION (REFER FIGURE 6)

D1X	LATERAL DISPLACEMENT BETWEEN RIGHT SIDEWALL OF CARBODY AND TOP OF LADING; B END OF CAR
D2X	LATERAL DISPLACEMENT BETWEEN RIGHT SIDEWALL OF CARBODY AND TOP OF LADING; CENTER OF CAR
D3X	LATERAL DISPLACEMENT BETWEEN RIGHT SIDEWALL OF CARBODY AND TOP OF LADING; A END OF CAR
A4Y	LONGITUDINAL ACCELERATION OF LADING ON TOP ALONG CENTERLINE; B END OF CAR
A5Z	VERTICAL ACCELERATION OF LADING ON TOP RIGHT SIDE; B END OF CAR
A6X	LATERAL ACCELERATION OF LADING ON TOP RIGHT SIDE; B END OF CAR
A7Z	VERTICAL ACCELERATION OF LADING ON TOP RIGHT SIDE; CENTER OF CAR
A8Z	VERTICAL ACCELERATION OF LADING ON TOP RIGHT SIDE; A END OF CAR
A9X	LATERAL ACCELERATION OF LADING ON TOP RIGHT SIDE; A END OF CAR
A10Y	LONGITUDINAL ACCELERATION OF CARBODY ON BOTTOM ALONG CENTERLINE; B END OF CAR
A11Z	VERTICAL ACCELERATION OF CARBODY ON BOTTOM RIGHT SIDE; B END OF CAR
A12X	LATERAL ACCELERATION OF CARBODY ON BOTTOM RIGHT SIDE; B END OF CAR
A13Z	VERTICAL ACCELERATION OF CARBODY ON BOTTOM LEFT SIDE; B END OF CAR
A14Z	VERTICAL ACCELERATION OF CARBODY ON BOTTOM RIGHT SIDE; A END OF CAR
A15X	LATERAL ACCELERATION OF CARBODY ON BOTTOM RIGHT SIDE; A END OF CAR
A16Z	VERTICAL ACCELERATION OF CARBODY ON BOTTOM LEFT SIDE; A END OF CAR
A17X	LATERAL ACCELERATION OF CARBODY ON TOP RIGHT SIDE; B END OF CAR
D18Z	ROLL DISPLACEMENT ALONG CENTERLINE OF CARBODY FLOOR; B END OF CAR
A19Z	VERTICAL ACCELERATION OF LEADING AXLE RIGHT SIDE (LTHD); A END OF CAR
A20X	LATERAL ACCELERATION OF LEADING AXLE RIGHT SIDE (LTHD); A END OF CAR
A21Z	VERTICAL ACCELERATION OF LEADING AXLE LEFT SIDE (LTHD); A END OF CAR

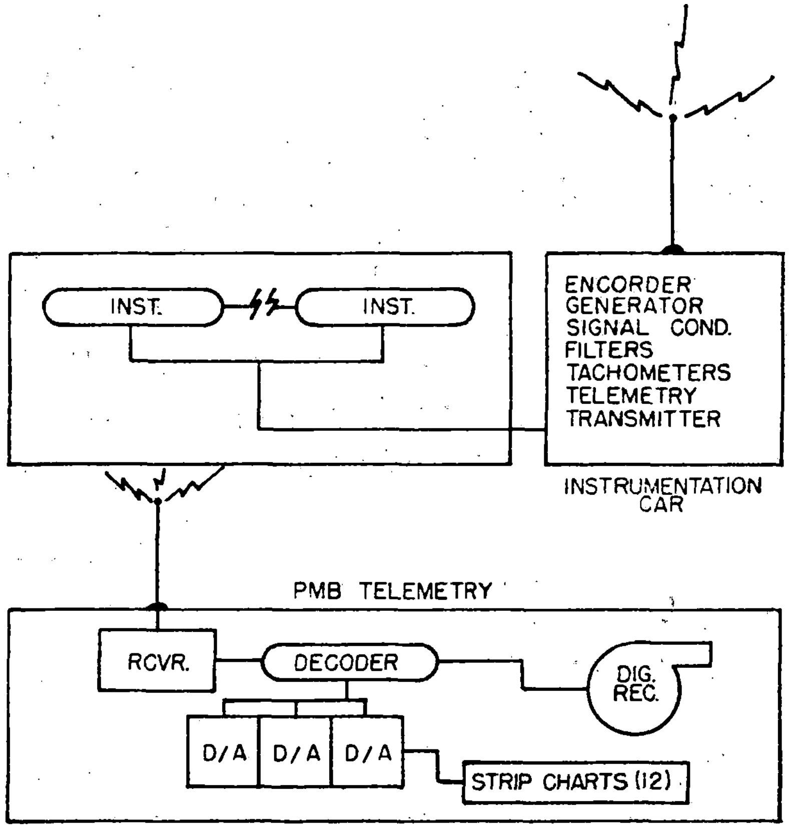


FIGURE 7. DATA ACQUISITION SCHEMATICS.

"Quick look" software was developed at the TTC, which processed the information acquired on digital magnetic tapes. With this software it was possible to look at the peak values, rms value, maximum and minimum value and average values of the acquired data. This mode of data processing enabled verification of successful data acquisition for each track test.

The validation testing data acquired on the VTU, with both forms of track geometry inputs, was processed in a way similar to that of track testing data. With the test vehicle placed on the VTU, all the measuring instruments on the test car were powered from the VTU instrumentation system with its bank of filters and signal conditioners. The transmitted signals from the Rail Dynamics Laboratory were received by the Telemetry Receiver at the PMB with the data recorded on the PDP 11/34 digital computer, low pass filtered at 30 Hz, and an array of strip charts.

The signal generation to drive the VTU with both forms of track geometry inputs was accomplished through the Profile Generation System (PGS) of the VTU's computer hardware, which consisted of outputting the input profile through twelve channels of digital-to-analog converters to the VTU. The signals were passed through the VTU analog control system to the voice coils of the servo valves controlling the actuator pistons that input the resultant vibratory forces to the vehicle under test. The analog data acquired from the different measuring devices on the test car were digitized and stored in buffers of the computer memory using analog-to-digital converters. The data acquisition computer acquired data continuously throughout a test.

TEST RESULTS AND DATA ANALYSIS

The data acquired during the track tests and the validation tests on the VTU were processed on PDP 11/60 computer. Frequency domain analysis was performed using the Data Reduction System (DRS) software developed at the TTC. Selected time slices pertaining to "roll" and "bounce" sections of the PTT and the corresponding VTU runs were processed using the "quick look" software. These time slices were created and stored as files in the User Data Base (UDB) format on the disk. The Data Reduction System (DRS) software accessed these files, performed Fast Fourier Transforms (FFT's) and PSD's on each block consisting of 1024 digital points. All blocks for each time slice were then added (power ensemble sum) and the resultant PSD plots were used for analysis. The validation made use of these PSD plots and the "real-time" time history (strip chart) records.

The analysis of data acquired on the track and VTU was divided into two sections. The first section dealt with the comparison of time history plots of LTHD accelerometers, both on the test track and on the VTU, at speeds of 15 mph and 50 mph. The second section dealt with the frequency domain analysis, comparing the PSD plots of LTHD accelerometers, lading accelerometers and carbody accelerometers on the test track and on the VTU.

The responses of the following accelerometers (shown in Figure 4) were subjected to the above analysis:

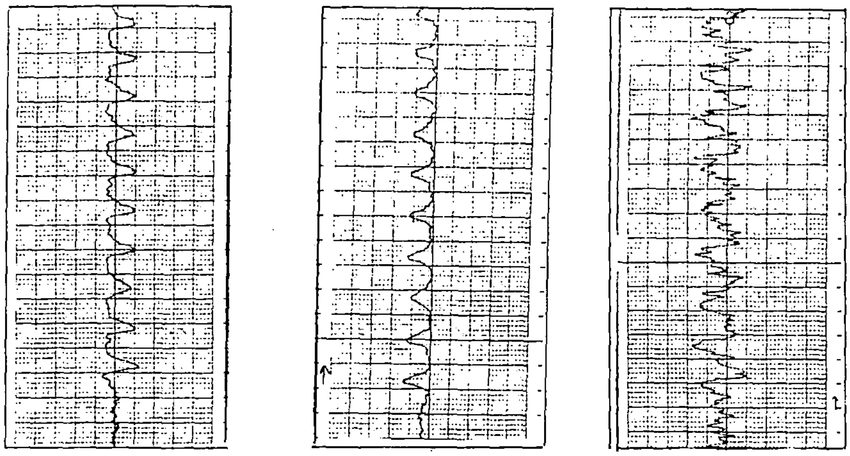
A 19Z, A 21Z, A 20X - LTHD accelerometers
A 5Z, A6X - Lading accelerometers
A 14Z, A 15X - Carbody accelerometers

(Note: Z and X represent vertical and lateral directions, respectively.)

The time history plots of the response of the axle mounted LTHD accelerometers on the VTU, with the two forms of input excitations to the VTU, were compared with the corresponding response on the track. These comparisons were made at 15 mph for the "roll" section with staggered joints and at 50 mph for the "bounce" section with parallel rail joints. Figures 8a, 8b and 8c present the responses of the axle-mounted sensors at 15 mph on the "roll" section. Figures 9a, 9b and 9c present the responses of the same accelerometers at 50 mph on the "bounce" section. It is evident from the wave shape of above time history plots that the response on the VTU with LTHD input is very much similar to that observed on the track in both "roll" and "bounce" modes. The response on the VTU with the Plasser input seemed to exhibit considerable "noise" due to reasons associated with the limitations of mid-chord offset data when converted into Space Curve Format as input for the VTU. Ref. 4 describes the probable reasons for the observed "noise" in the VTU response with the reformatted Plasser input.

It was noticed that the amplitude of the response with the LTHD input to the VTU was reduced by a factor of 20%, possibly due to scaling errors during the reformatting process of LTHD space curves. (This reduction in amplitude was observed only for the response of LTHD vertical accelerometers.) The error in the LTHD vertical input to the VTU was alleviated by conducting a test with 20% increase in gain for vertical actuators of the VTU. Figure 10 shows the corresponding responses on the VTU with the enhanced LTHD input compared with

Fig. 8a
A19Z

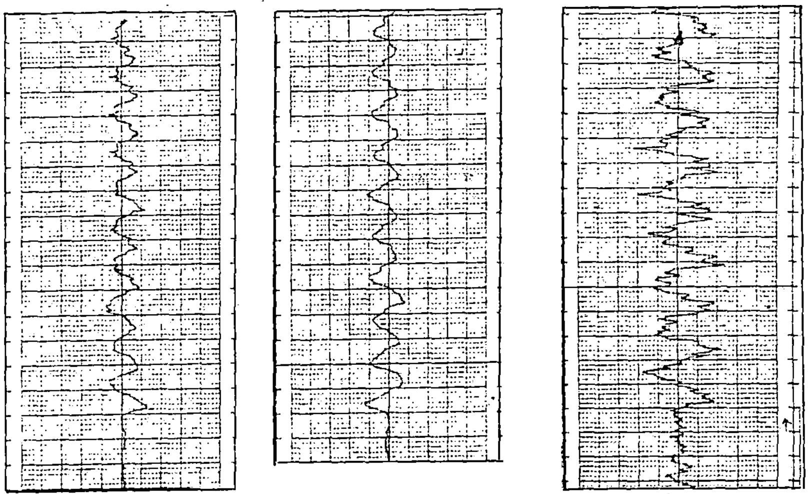


TRACK RESPONSE
SCALE 100 MV/Div.

VTU RESPONSE-
LTHD INPUT
SCALE 100 MV/Div.

VTU RESPONSE-
PLASSER INPUT
SCALE 50 MV/Div.

Fig. 8b
A20X

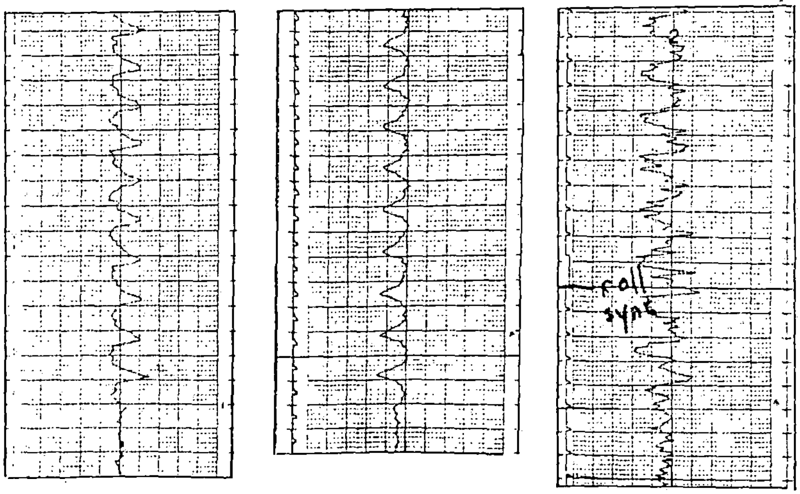


TRACK RESPONSE
SCALE 100MV/Div.

VTU RESPONSE-
LTHD INPUT
SCALE 100MV/Div.

VTU RESPONSE-
PLASSER INPUT
SCALE 50 MV/Div.

Fig. 8c
A21Z



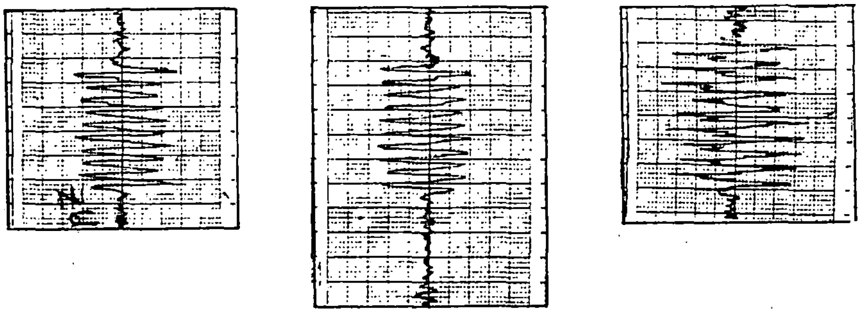
TRACK RESPONSE
SCALE 100 MV/Div.

VTU RESPONSE-
LTHD INPUT
SCALE 100 MV/Div.

VTU RESPONSE-
PLASSER INPUT
SCALE 50 MV/Div.

FIGURES 8a, 8b & 8c. REAL-TIME STRIP CHART RECORDS OF AXLE-MOUNTED ACCELEROMETERS A19Z, A20X AND A21Z FOR 15 MPH RUNS ON THE ROLL SECTION OF THE PTT.

Fig. 9a
A19Z

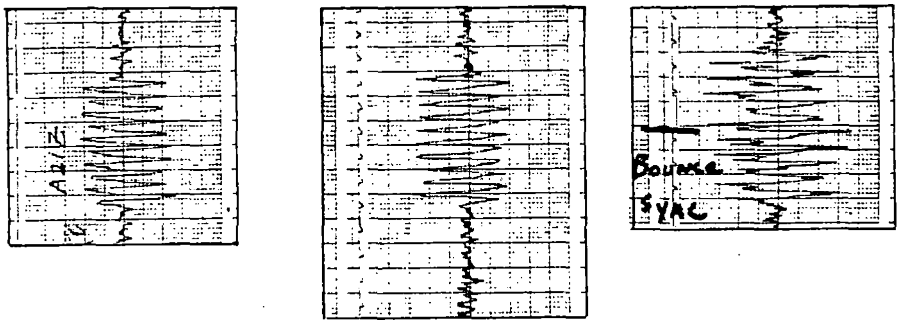


TRACK RESPONSE
SCALE 100 MV/Div.

VTU RESPONSE-
LTHD INPUT
SCALE 100 MV/Div.

VTU RESPONSE
PLASSER INPUT
SCALE 50 MV/Div.

Fig. 9b
A20X

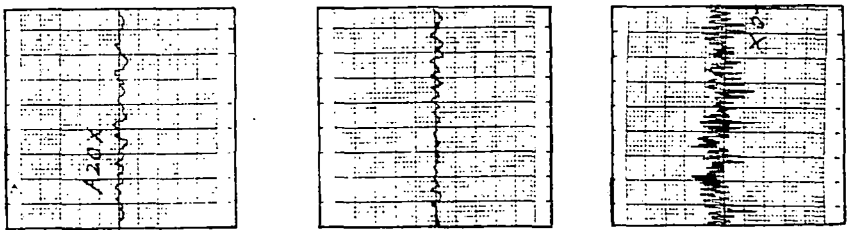


TRACK RESPONSE
SCALE 100 MV/ Div.

VTU RESPONSE-
LTHD INPUT
SCALE 100 MV/ Div.

VTU RESPONSE-
PLASSER INPUT
SCALE 50 MV/ Div.

Fig. 9c
A21Z



TRACK RESPONSE
SCALE 100 MV/ Div.

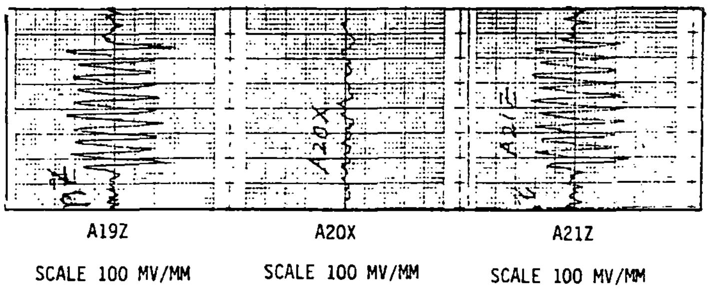
VTU RESPONSE-
LTHD INPUT
SCALE 100 MV/ Div.

VTU RESPONSE-
PLASSER INPUT
SCALE 50 MV/Div.

FIGURES 9a, 9b & 9c. REAL-TIME STRIP CHART RECORDS OF AXLE-MOUNTED ACCELEROMETERS A19Z, A21Z AND A20X FOR 50 MPH RUNS ON THE BOUNCE SECTION OF THE PTT.

the responses on the track. A considerable improvement in the agreement of the VTU response with the track response, both in wave shape and amplitude, was obtained with the 20% gain increase for the vertical actuators. It can be inferred from the above analysis of time history plots that (with slight modification of LTHD conversion process) it is possible to achieve a realistic response on the VTU, compared to the vehicle response on the actual track.

Track Response of LTHD Accelerometers at 50 mph on Bounce Section



Response on the VTU with LTHD Input and 20 Percent Increase in Gain for Vertical Actuators (for 50 mph Run on Bounce Section)

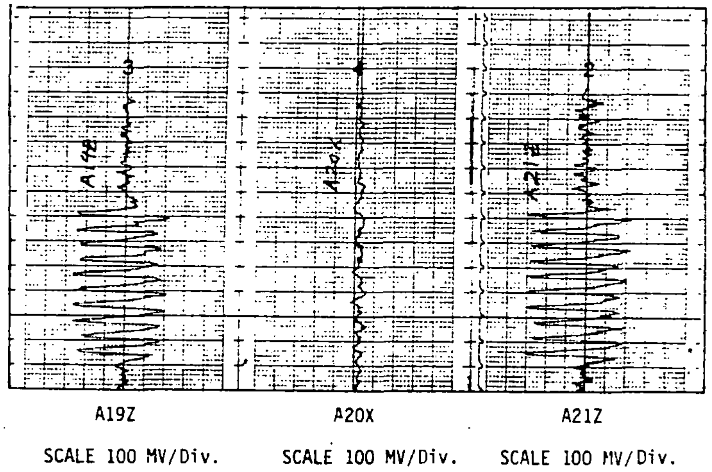


FIGURE 10. SIMILARITY BETWEEN TRACK RESPONSE AND THE RESPONSE ON THE VTU (WITH 20% INCREASE IN GAIN FOR VTU VERTICAL ACTUATORS).

Another minor aspect of the LTHD accelerometer response strip chart data is that the waveform has a switched polarity in the case of the VTU-LTHD input runs, as compared to the track and VTU-Plasser input runs. This reverse polarity was also induced during the reformatting process of LTHD space curves and does not hamper any analysis or comparison efforts, although a correction for this reversal needs to be made in creating the PGS input tapes for future testing.

Frequency domain analysis was comprised of overlaying PSD plots of seven different response channels of the test vehicle (viz., 3 LTHD, 2 lading and 2 carbody accelerometers), acquired on the test track and on the VTU with Plasser and LTHD inputs. Figures 11 through 16 present overlays of the PSD plots of the lading, carbody, and LTHD accelerometers comparing the track

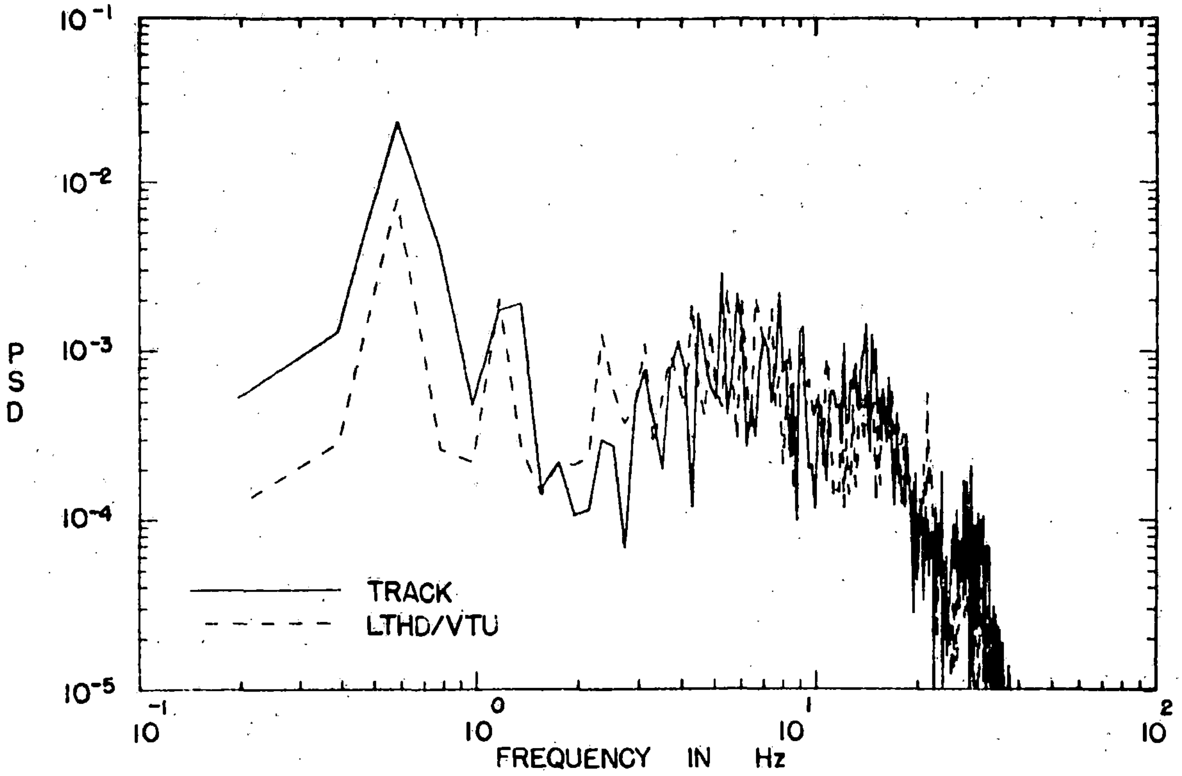


FIGURE 11. COMPARISON OF A5Z AT 15 MPH, PTT ROLL SECTION, LADING (VERTICAL) ACCELEROMETER.

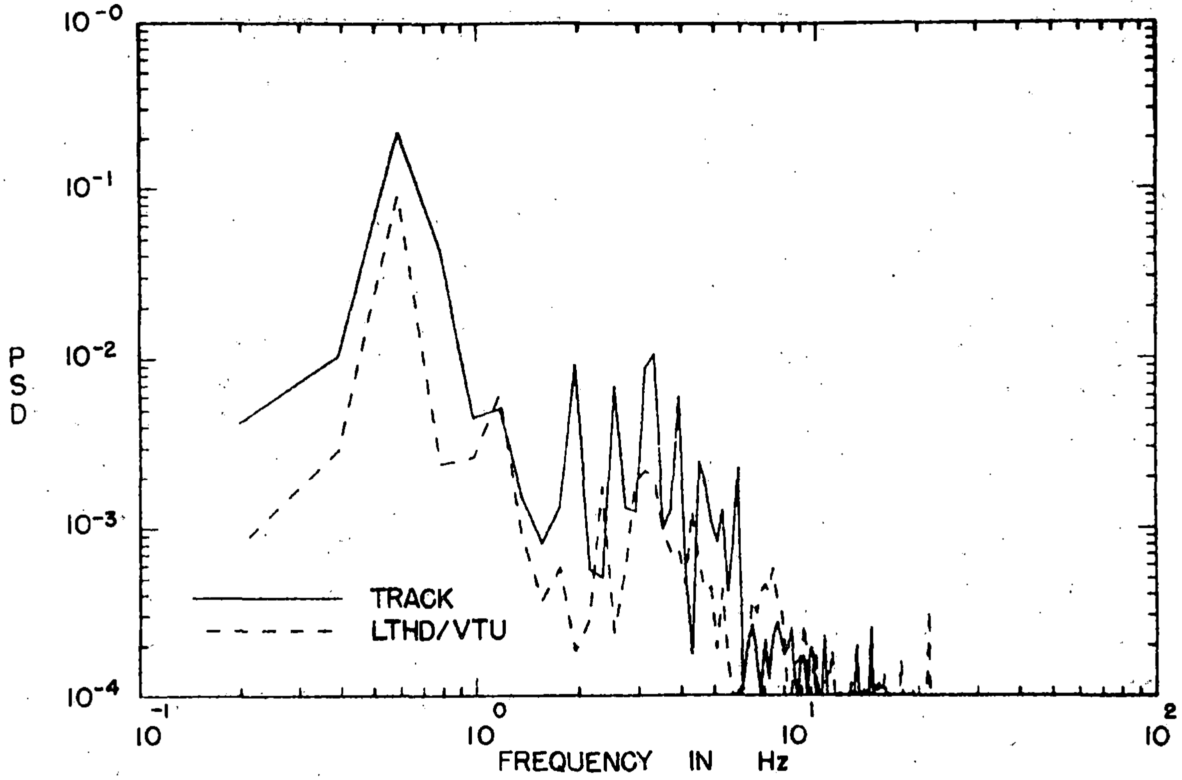


FIGURE 12. COMPARISON OF A6X AT 15 MPH, PTT ROLL SECTION, LADING (LATERAL) ACCELEROMETER.

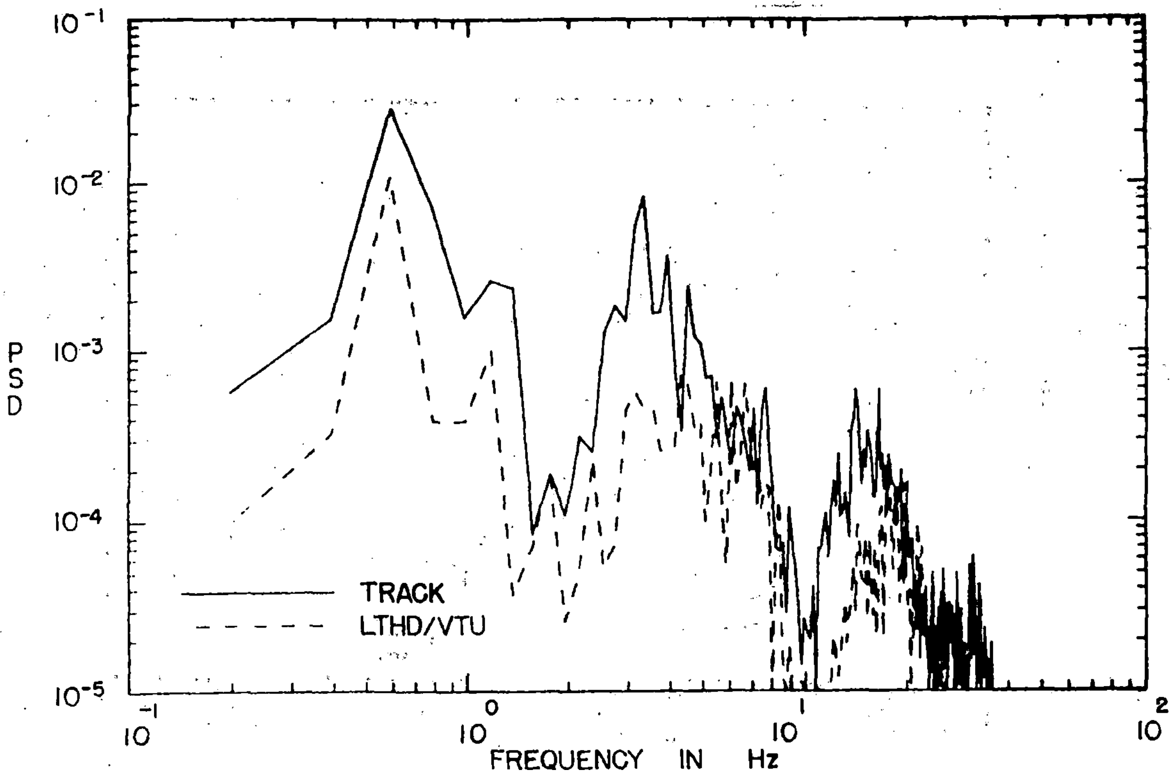


FIGURE 13. COMPARISON OF A14Z AT 15 MPH, PTT ROLL SECTION, CARBODY (VERTICAL) RESPONSE.

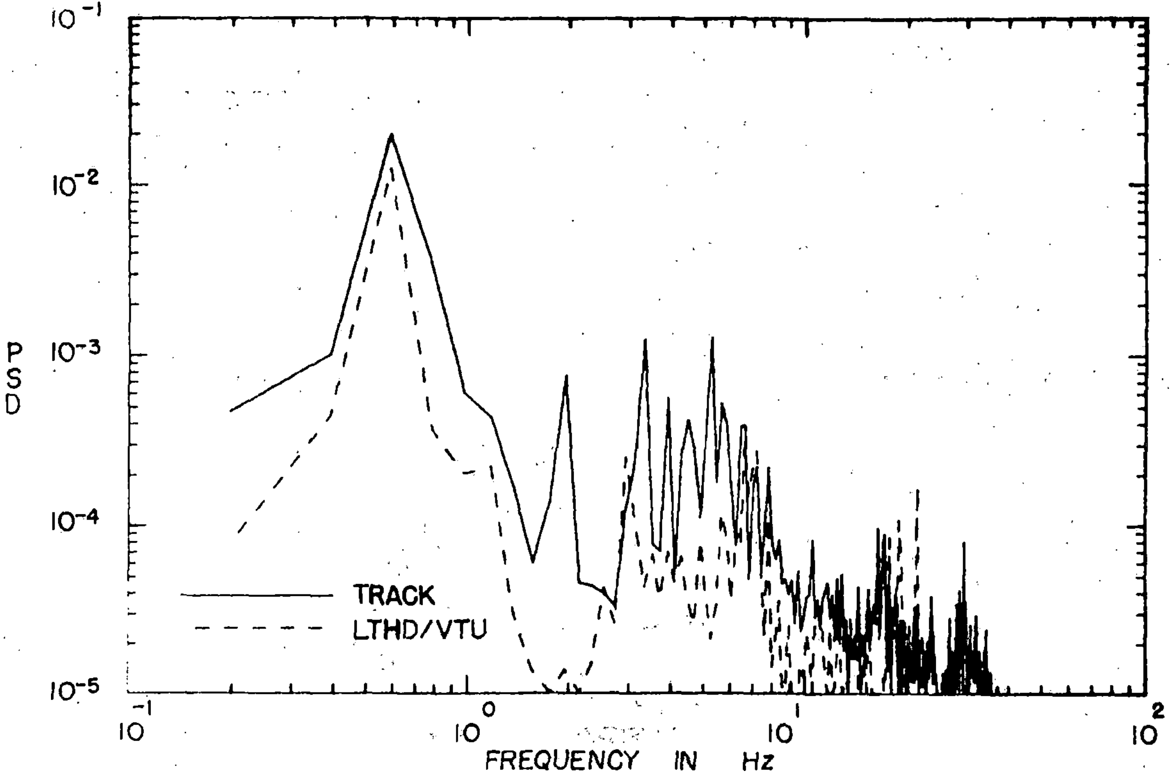


FIGURE 14. COMPARISON OF A15X AT 15 MPH, PTT ROLL SECTION, CARBODY (LATERAL) RESPONSE.

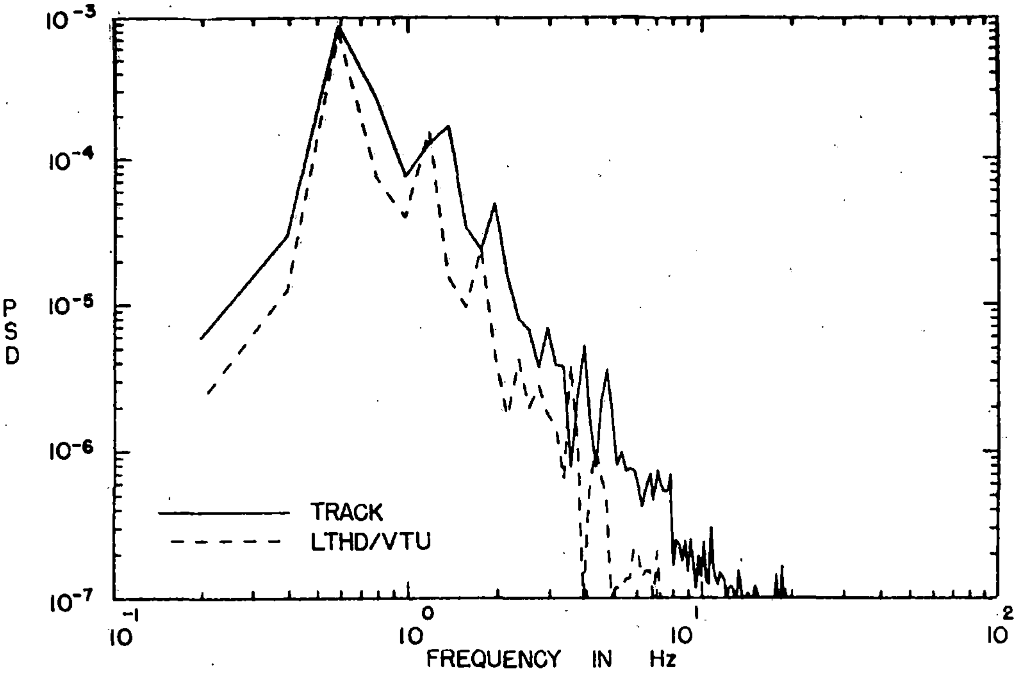


FIGURE 15. COMPARISON OF A19Z AT 15 MPH, PTT ROLL SECTION, AXLE-MOUNTED LTHD ACCELEROMETER (VERTICAL) RESPONSE.

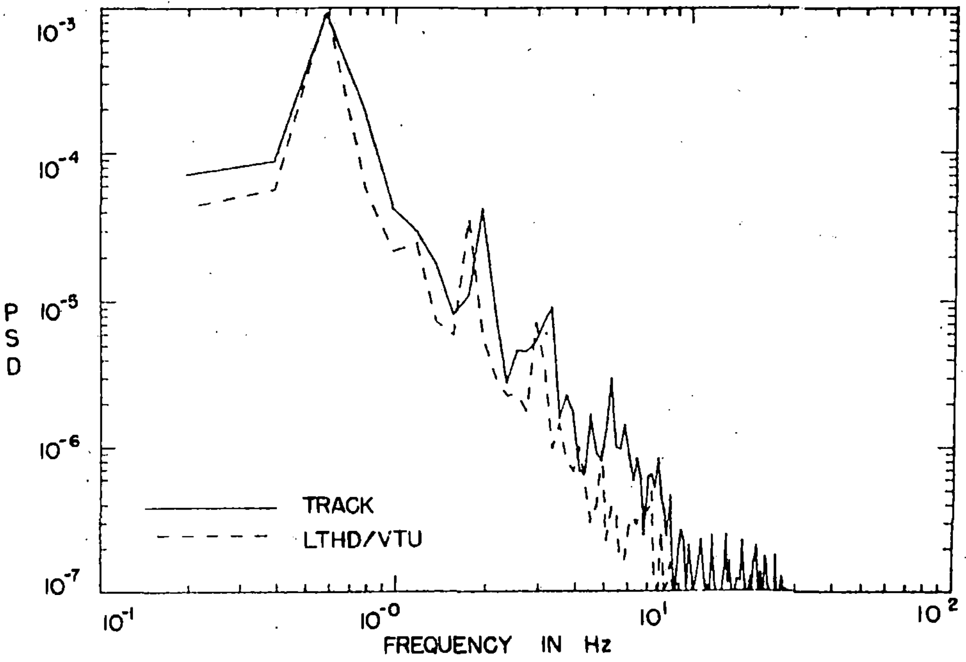


FIGURE 16. COMPARISON OF A20X AT 15 MPH, PTT ROLL SECTION, AXLE-MOUNTED LTHD ACCELEROMETER (LATERAL) RESPONSE.

response with the response on the VTU (with LTHD input) at an equivalent speed of 15 mph on the roll section. Figures 17 through 22 present overlays of similar PSD plots for the lading, carbody, and LTHD accelerometers with the Plasser input to the VTU at a speed of 15 mph on the roll section. Figures 23 through 29 show similar comparisons at 50 mph for the bounce section for the track and LTHD-VTU runs. Figures 30 through 35 present similar comparisons at 50 mph for the bounce section for the track and Plasser-VTU runs.

A point worth noting before analyzing these plots is that the slight shift in frequency, as noticed between the LTHD and track PSD's around the fundamental track joint frequency, is due to the speed of the two inputs not being identical. In other words, the locomotive speed on the track for a nominal 15 or 50 mph run varied by as much as 2 to 3 mph of the scheduled speeds. When the VTU runs were made using the LTHD as input, the playback speeds were not changed to match the actual track speeds. However, the speeds were matched for the VTU runs using Plasser as input. Thus, the peaks in the lower frequency range correlate well as seen from the PSD plots for the track and Plasser runs.

The following observations are drawn from the frequency domain analysis of track geometry input validation tests:

1. At 15 mph (roll section), the response on the VTU with both Plasser and LTHD inputs shows good correlation with the actual track response up to a frequency level of 4 Hz. Beyond 4 Hz, the PSD plots show more "noise" associated with the response on the VTU with Plasser input. The PSD's of LTHD-VTU runs show very good agreement with those of actual track runs for all channels.

2. At 50 mph (bounce section), the respone data for Plasser-VTU runs show a considerable lack of agreement with the actual track data beyond frequency levels of 2 Hz. These discrepancies are more evident for lateral acceleration of the front axle (A20X). Plasser-VTU runs produce incorrect peaks as seen from PSD's at frequencies beyond 2 Hz.

3. At 50 mph, LTHD-VTU data compare well with the track response data in frequency content as well as PSD amplitude levels.

CONCLUSIONS AND RECOMMENDATIONS

The reformatted LTHD input to the VTU offers a wide range of possibilities to reproduce realistic vehicle responses on the VTU. The reason for the slight change in the gain of vertical input, and the reversed polarity of both lateral and vertical inputs needs to be investigated and corrected in the conversion process. The reformatted LTHD space curves, as an appropriate track geometry input to the VTU, accentuates the capability of the VTU as the most promising means of reproducing track conditions for sustained periods of testing, especially for lading damage and component fatigue evaluation under controlled conditions.

At lower speeds (15 mph and below), the reformatted Plasser input to the VTU does show good agreement with the response of the actual track at frequency levels lower than 2 Hz. As the speed increases, the Plasser-VTU runs show considerable deterioration in agreement with actual track run in terms of PSD amplitude level as well as frequency content. The lack of agreement is more

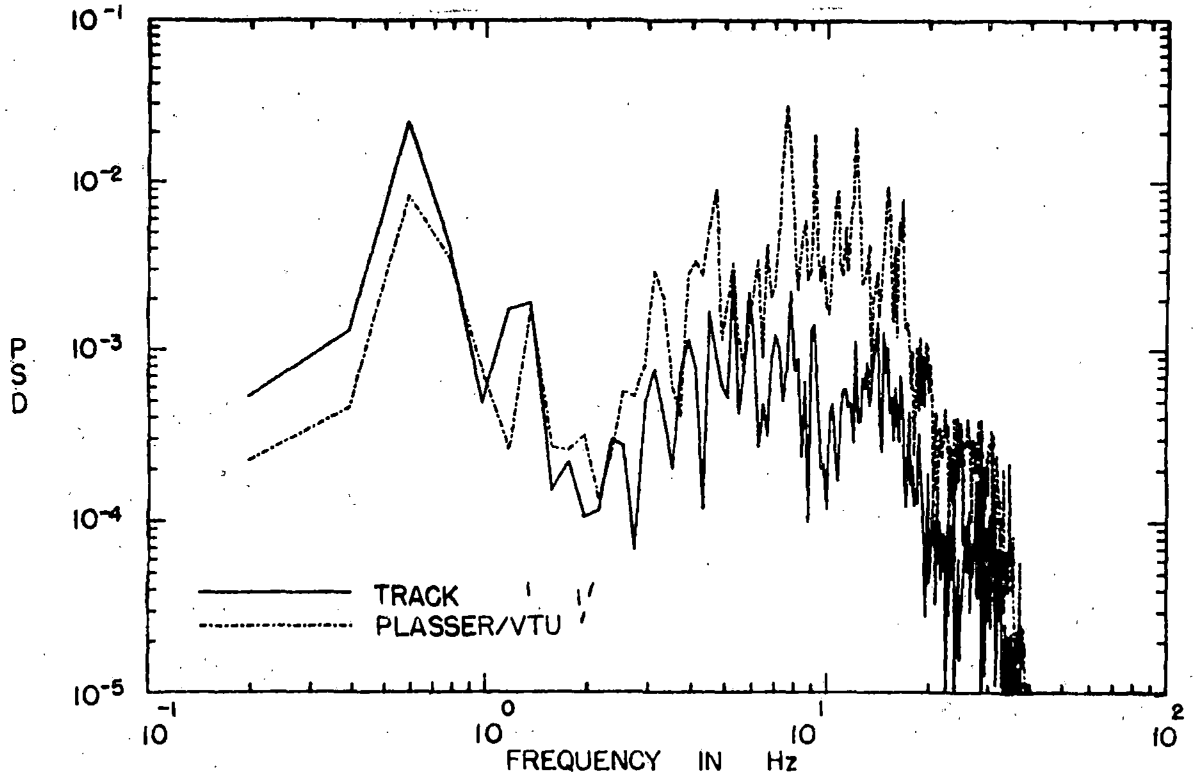


FIGURE 17. COMPARISON OF A5Z AT 15 MPH, PTT ROLL SECTION, LADING (VERTICAL) RESPONSE.

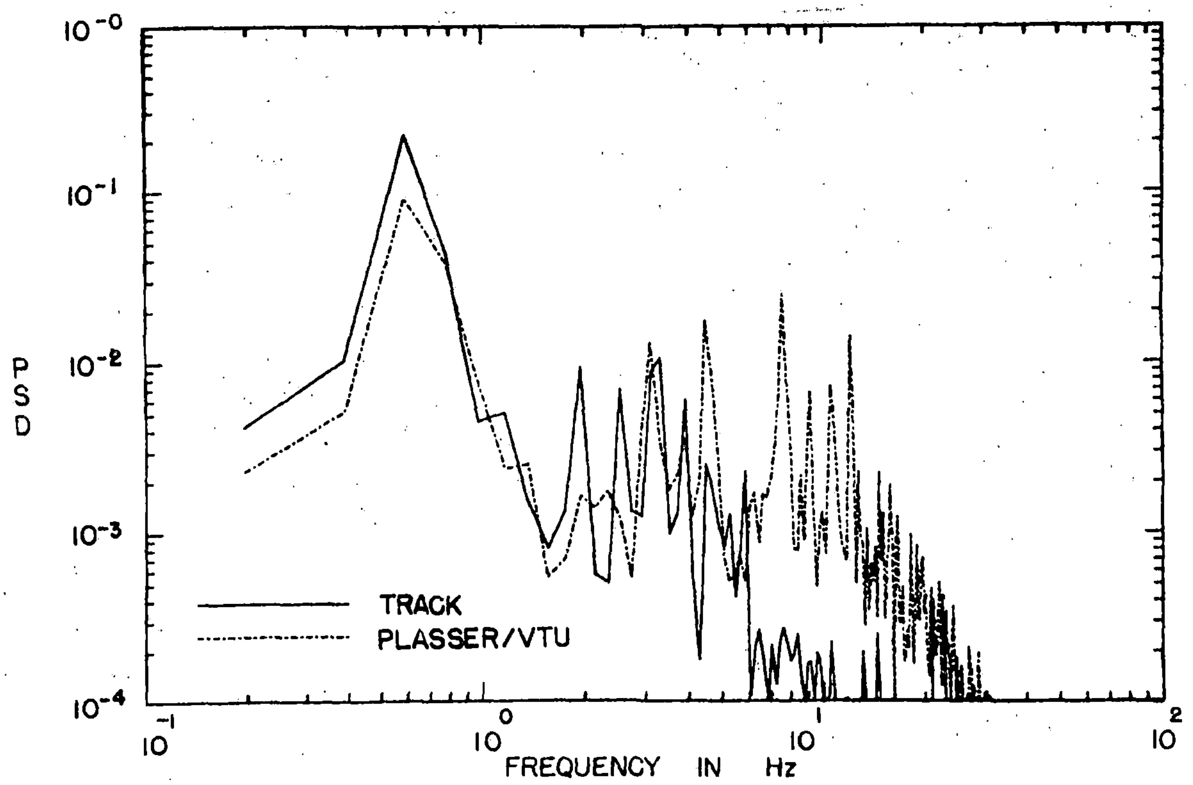


FIGURE 18. COMPARISON OF A6X AT 15 MPH, PTT ROLL SECTION, LADING (LATERAL) RESPONSE.

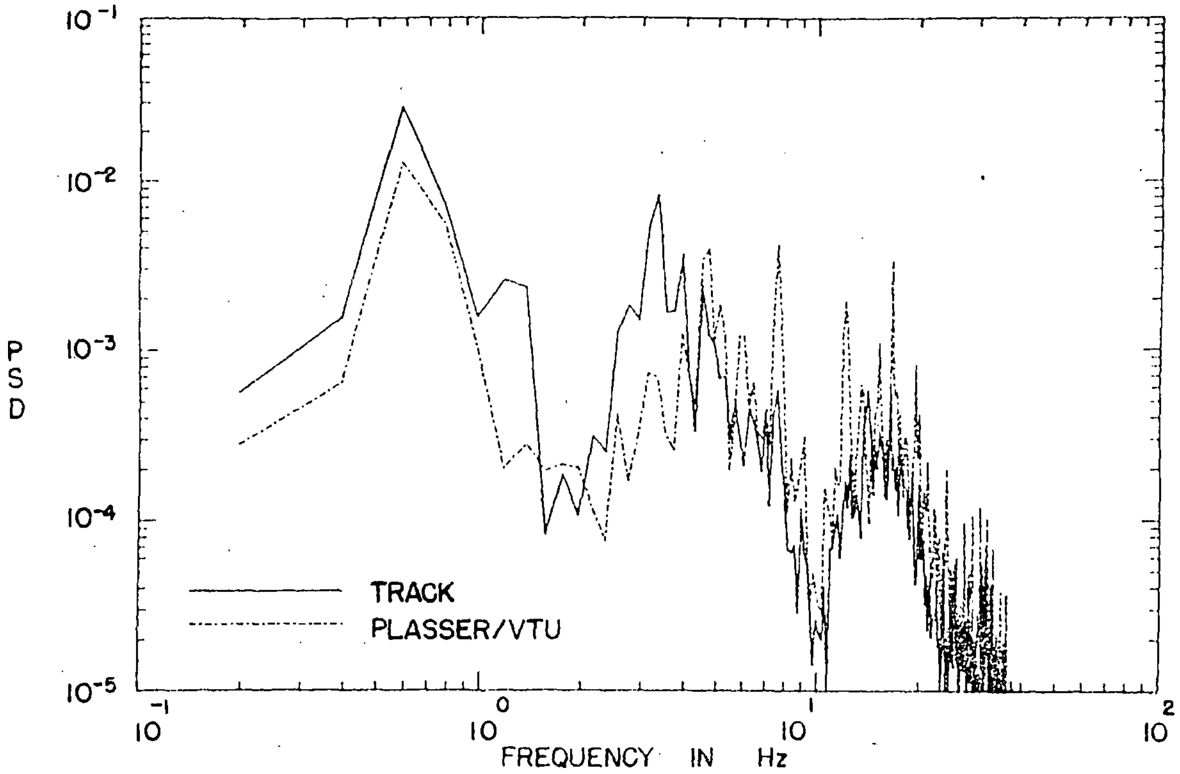


FIGURE 19. COMPARISON OF A14Z AT 15 MPH, PTT ROLL SECTION, CARBODY (VERTICAL) RESPONSE.

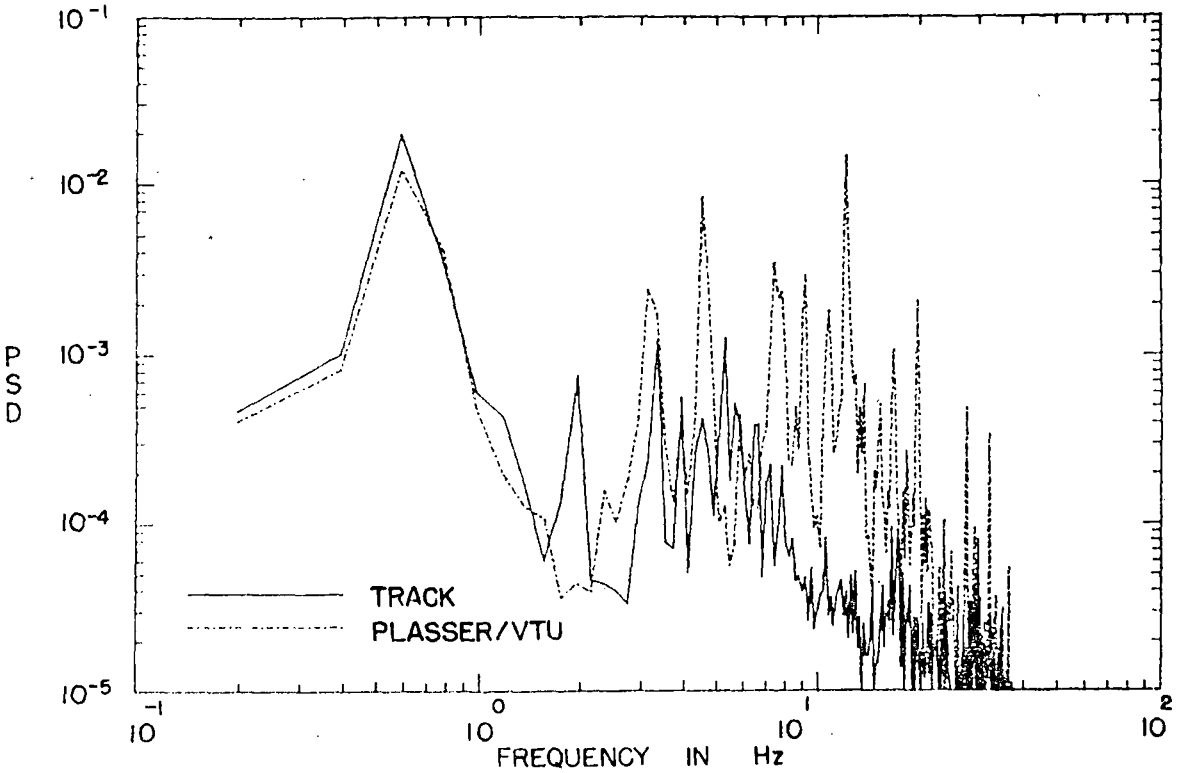


FIGURE 20. COMPARISON OF A15X AT 15 MPH, PTT ROLL SECTION, CARBODY (LATERAL) RESPONSE.

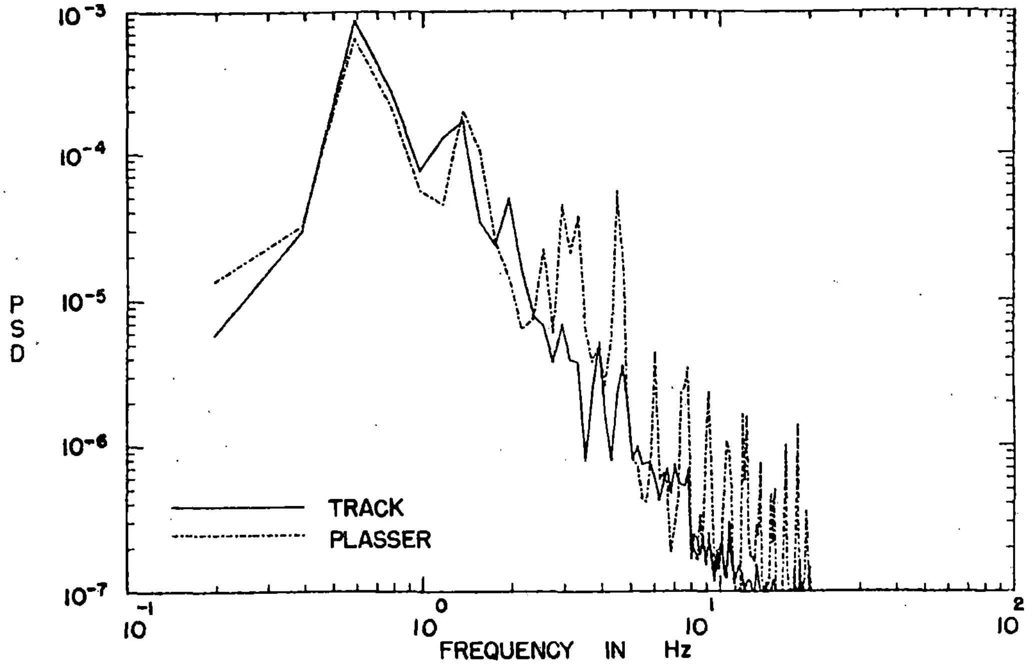


FIGURE 21. COMPARISON OF A19Z AT 15 MPH, PTT ROLL SECTION, AXLE-MOUNTED LTHD ACCELEROMETER RESPONSE.

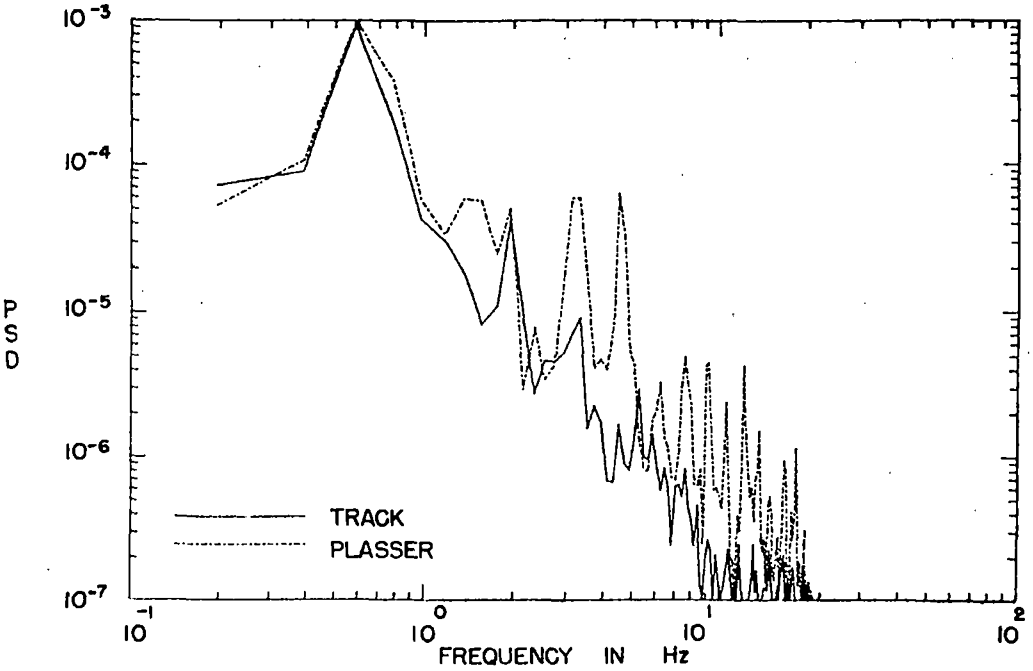


FIGURE 22. COMPARISON OF A20X AT 15 MPH, PTT ROLL SECTION, AXLE-MOUNTED LTHD ACCELEROMETER RESPONSE.

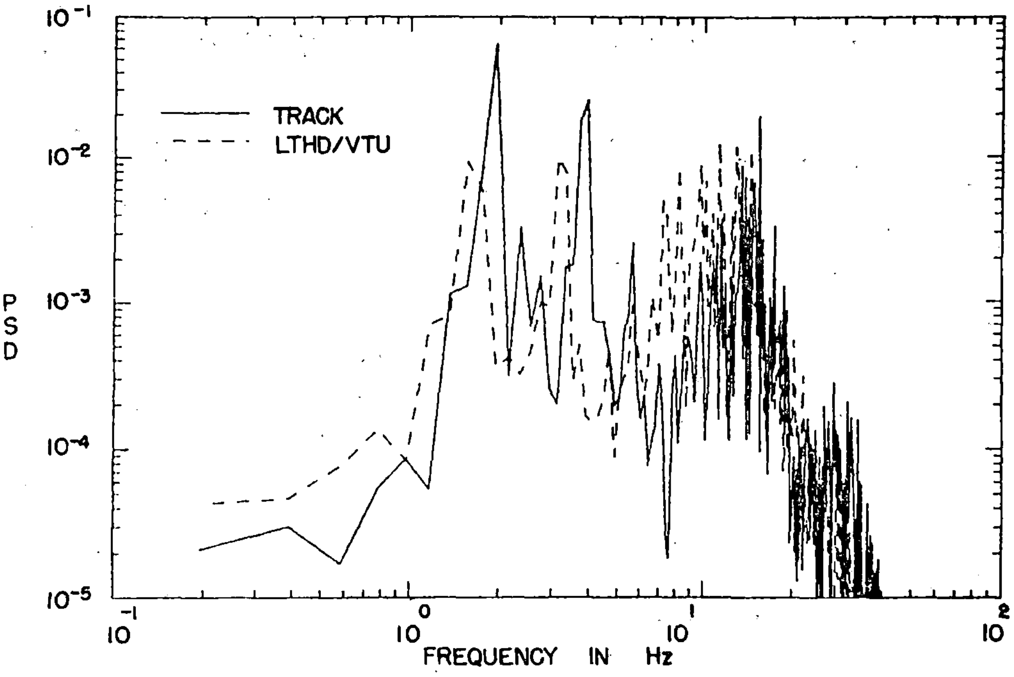


FIGURE 23. COMPARISON OF A5Z AT 50 MPH, PTT BOUNCE SECTION, LADING (VERTICAL) RESPONSE.

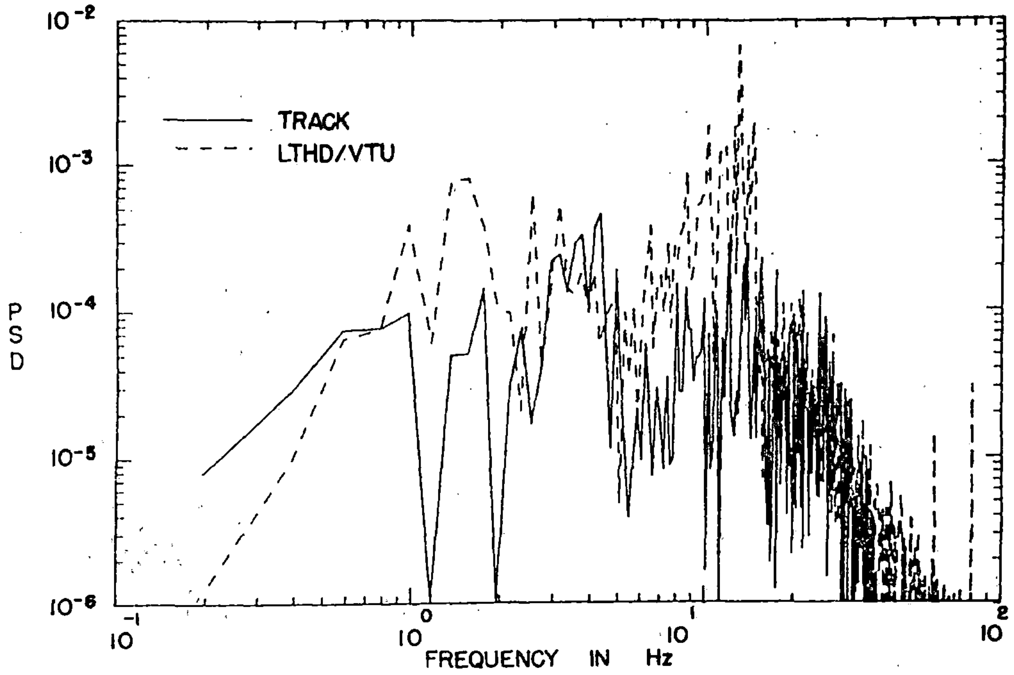


FIGURE 24. COMPARISON OF A6X AT 50 MPH, PTT BOUNCE SECTION, LADING (LATERAL) RESPONSE.

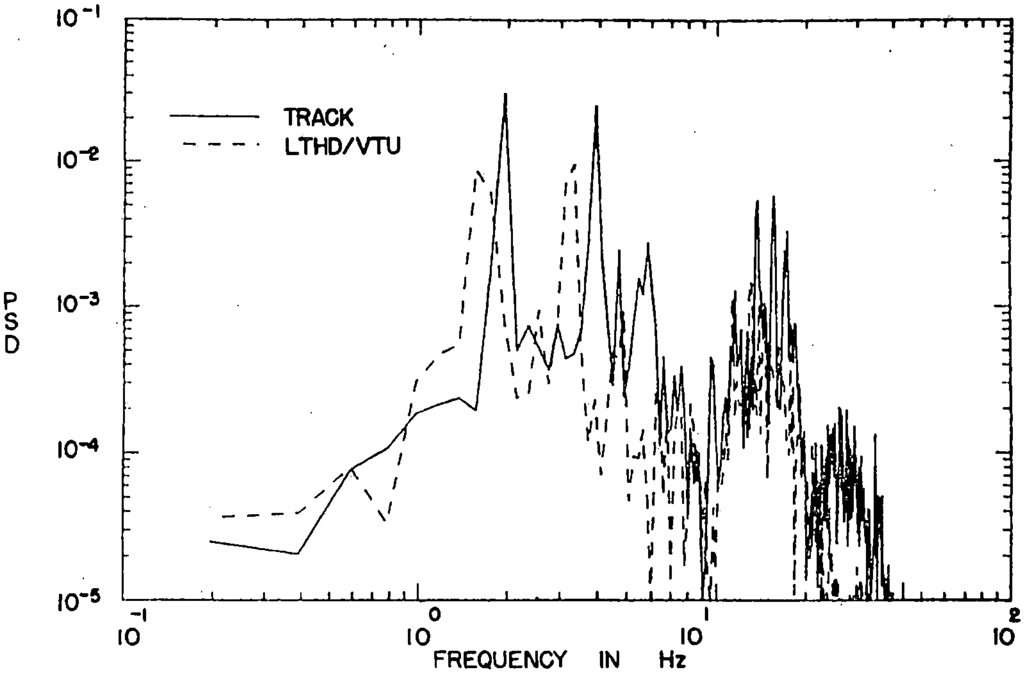


FIGURE 25. COMPARISON OF A14Z AT 50 MPH, PTT BOUNCE SECTION, CARBODY (VERTICAL) RESPONSE.

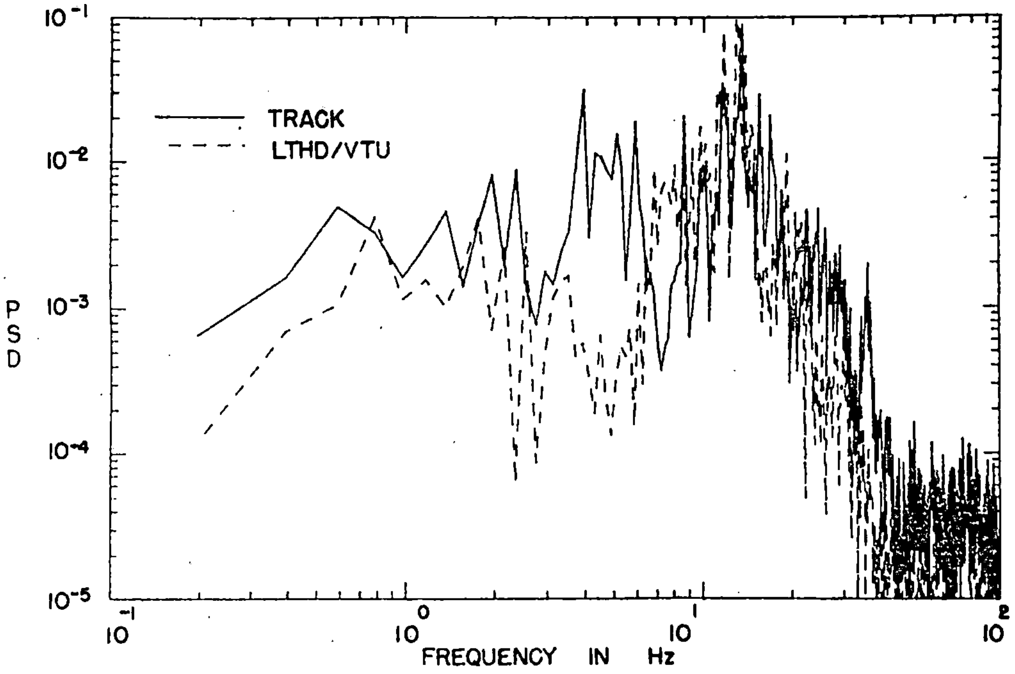


FIGURE 26. COMPARISON OF A15X AT 50 MPH, PTT BOUNCE SECTION, CARBODY (LATERAL) RESPONSE.

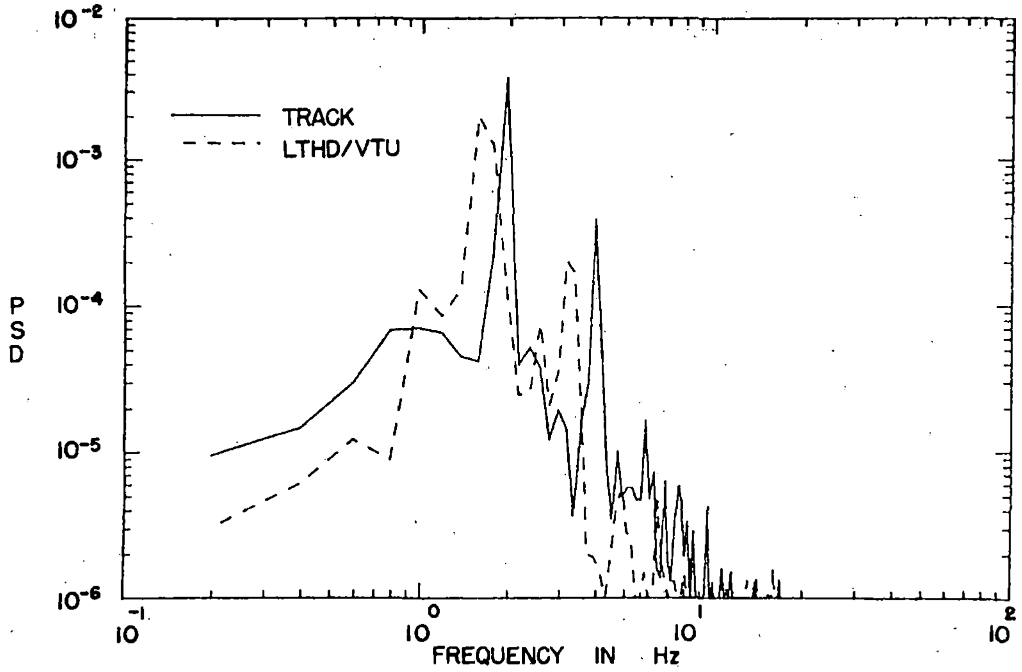


FIGURE 27. COMPARISON OF A19Z AT 50 MPH, PTT BOUNCE SECTION, AXLE-MOUNTED LTHD ACCELEROMETER (VERTICAL) RESPONSE.

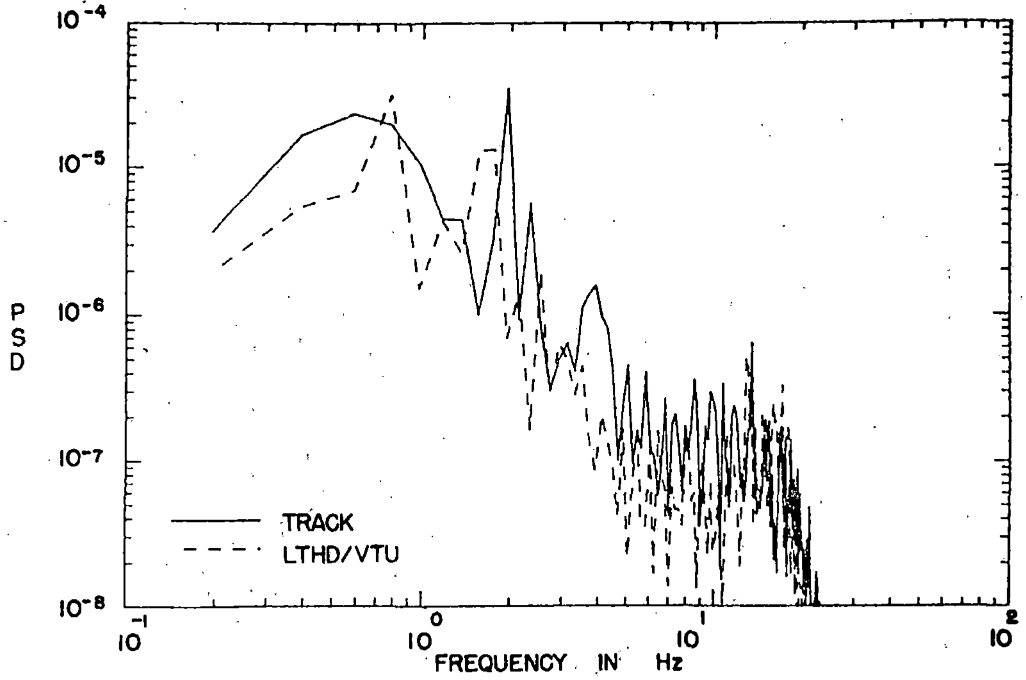


FIGURE 28. COMPARISON OF A20X AT 50 MPH, PTT BOUNCE SECTION, AXLE-MOUNTED LTHD ACCELEROMETER (LATERAL) RESPONSE.

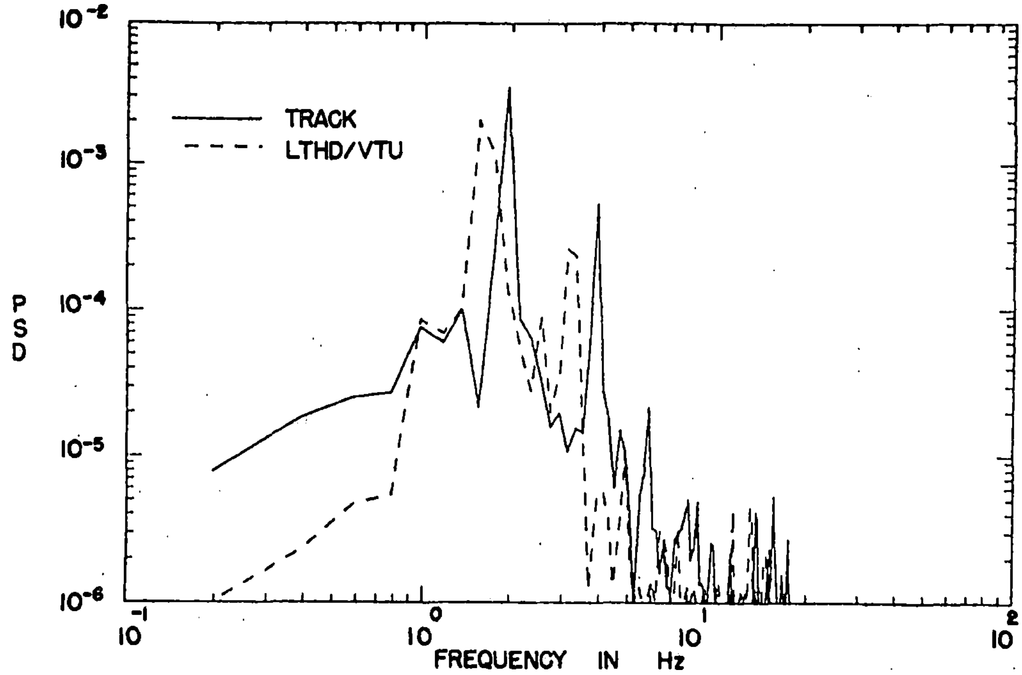


FIGURE 29. COMPARISON OF A21Z AT 50 MPH, PTT BOUNCE SECTION, AXLE-MOUNTED LTHD ACCELEROMETER (VERTICAL) RESPONSE.

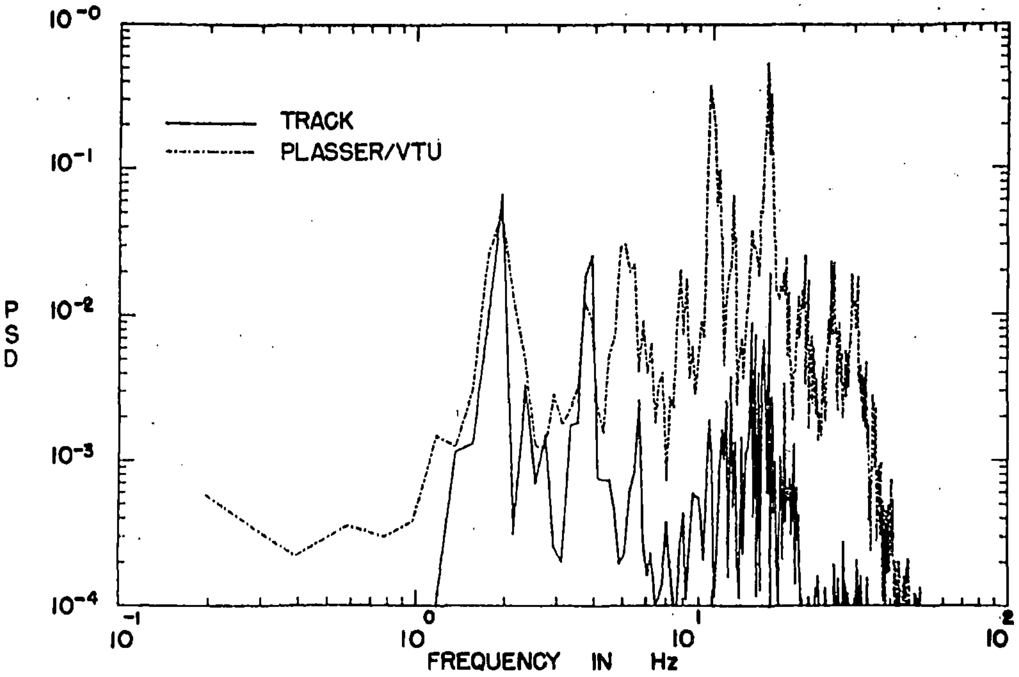


FIGURE 30. COMPARISON OF A5Z AT 50 MPH, PTT BOUNCE SECTION, LADING RESPONSE.

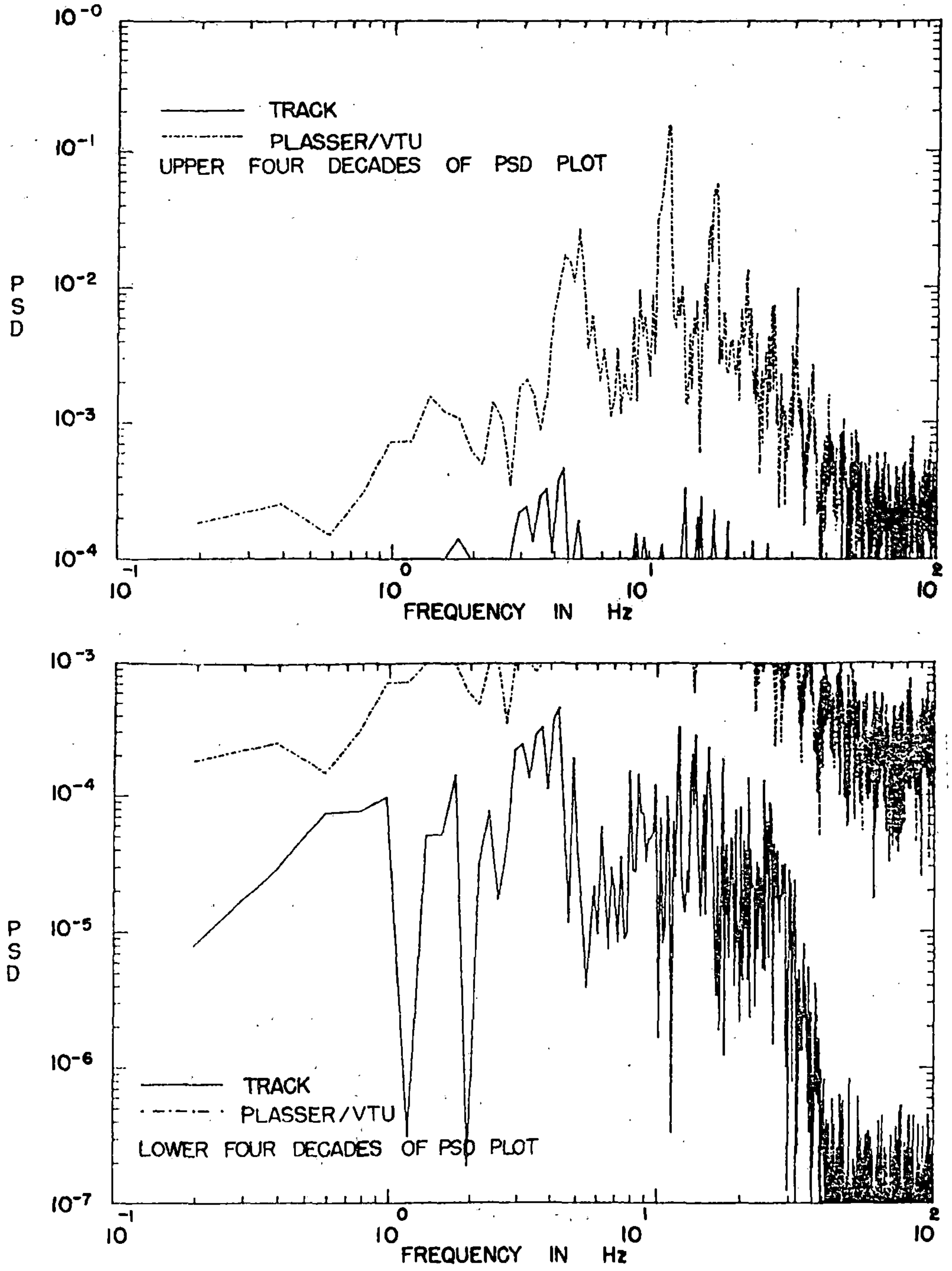


FIGURE 31. COMPARISON OF A6X AT 50 MPH, PTT BOUNCE SECTION, LADING (LATERAL) RESPONSE.

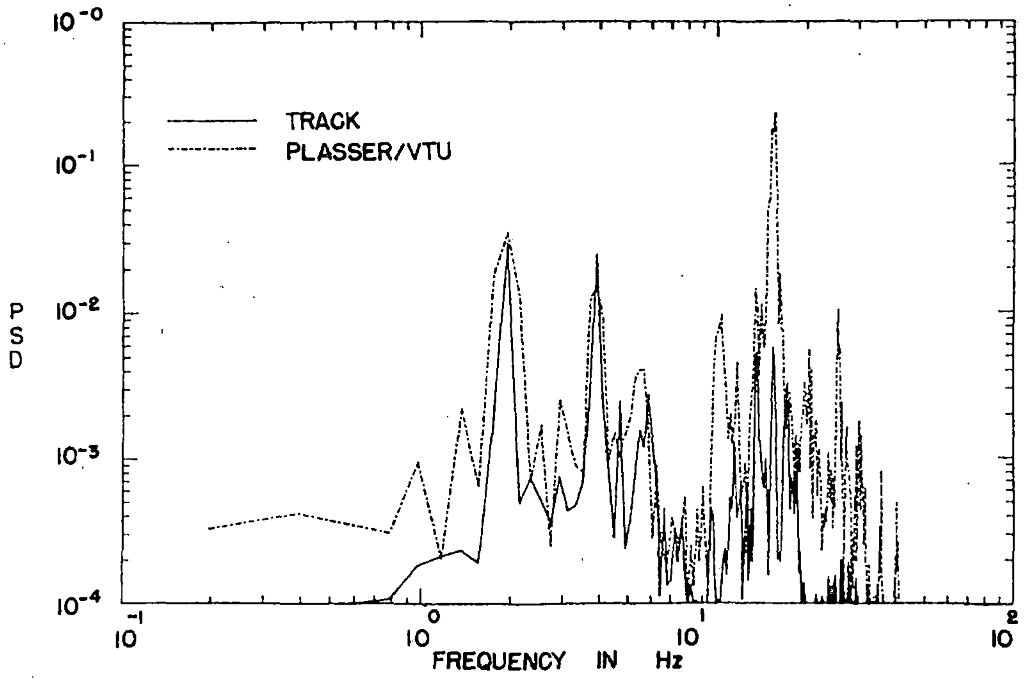


FIGURE 32. COMPARISON OF A14Z AT 50 MPH, PTT BOUNCE SECTION, CARBODY (VERTICAL) RESPONSE.

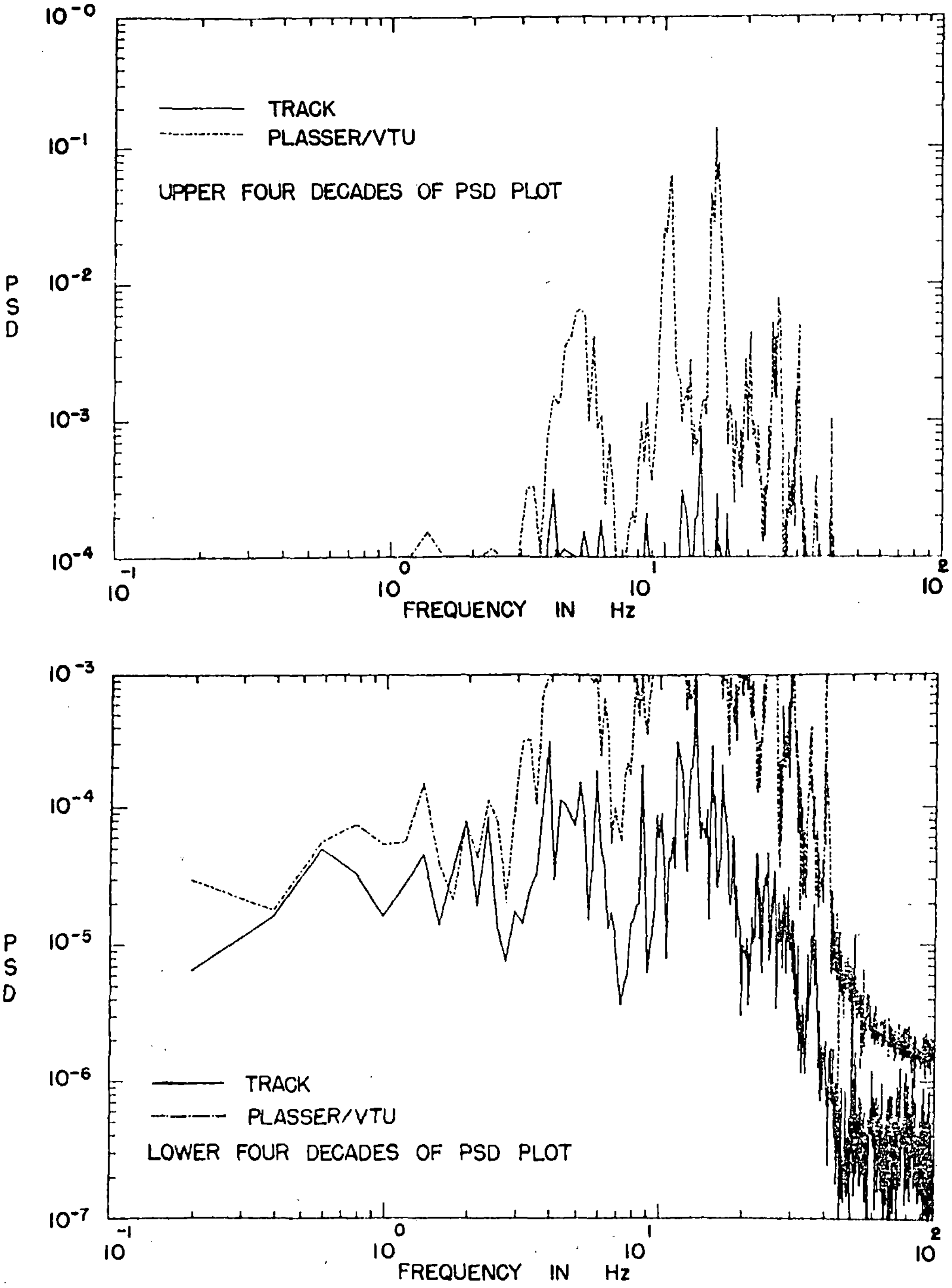


FIGURE 33. COMPARISON OF A15X AT 15 MPH, PTT BOUNCE SECTION, CARBODY (LATERAL) RESPONSE.

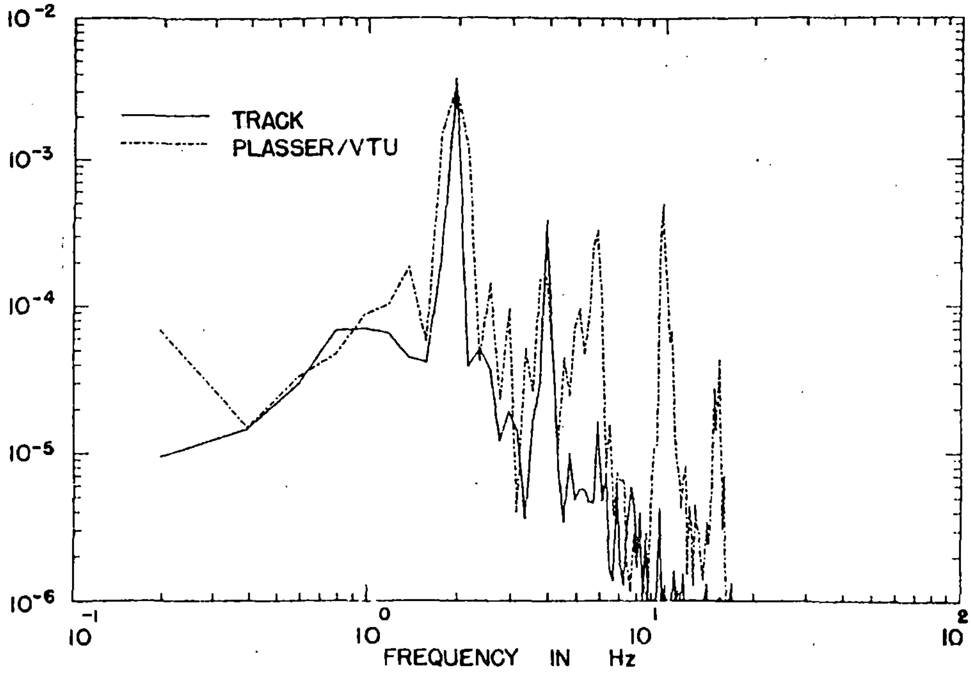


FIGURE 34. *COMPARISON OF A19Z AT 15 MPH, PTT BOUNCE SECTION, AXLE-MOUNTED LTHD ACCELEROMETER (VERTICAL) RESPONSE.*

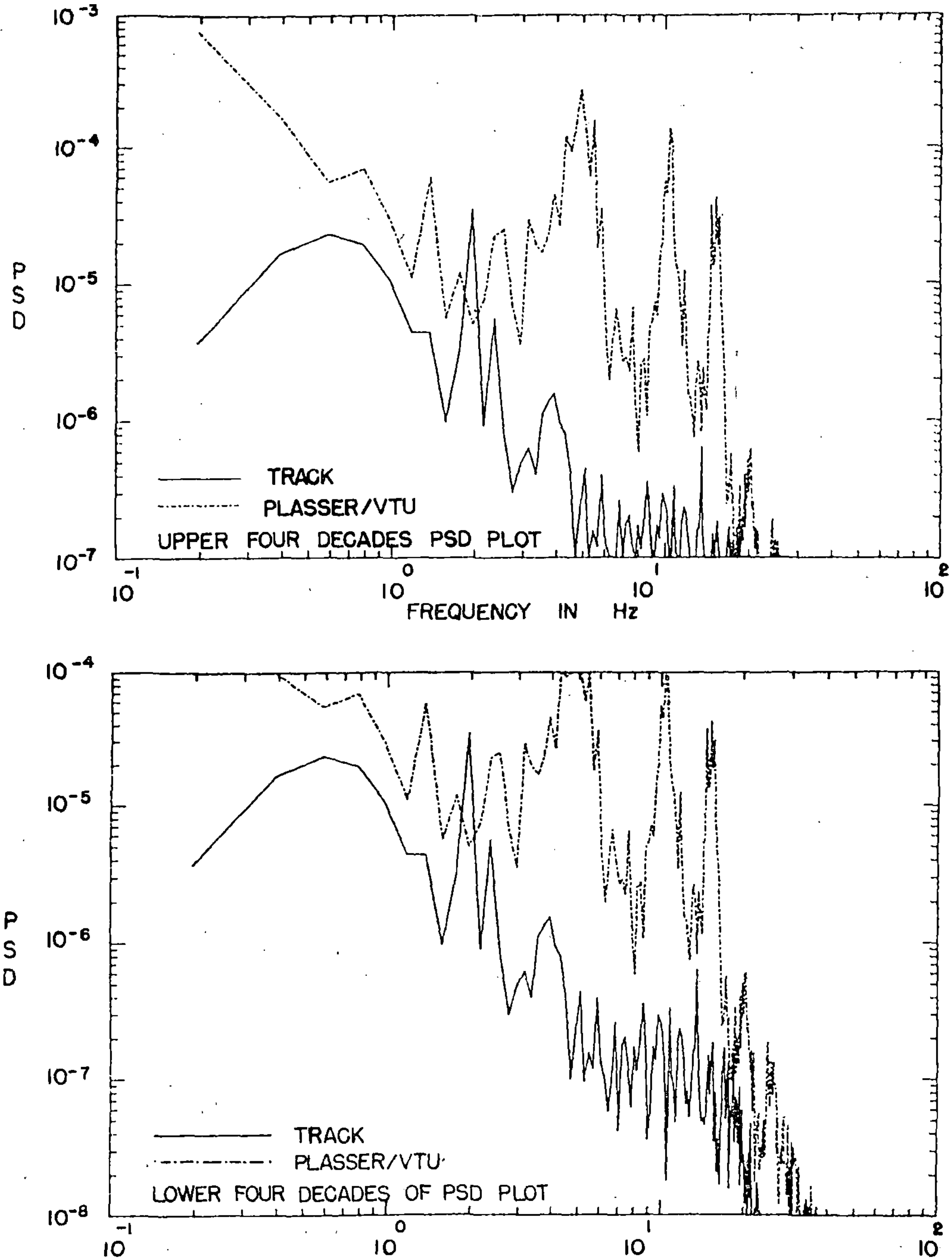


FIGURE 35. COMPARISON OF A20X AT 15 MPH, PTT BOUNCE SECTION, AXLE-MOUNTED LTHD ACCELEROMETER (LATERAL) RESPONSE.

pronounced with the measured response of the axle-mounted lateral accelerometer. The discrepancies are attributed to limitations in the basic Plasser measurement technique for use in any practical space curve construction algorithm. The MITRE Corporation has suggested certain measures which could be taken to alleviate the above source of noise. Some improvements are suggested for the existing data by using high-pass cross level and gage signals, and matrixing them with mean profile (½ left + ½ right) and mean alignment, respectively, to get the required VTU driving signals. More testing is recommended after these improvements are incorporated in the reformatted Plasser tapes, to make an assessment of their viability as a realistic input excitation to the VTU. This possibility indeed would provide a more readily available source of alternate track inputs to the VTU to enable it to become the most viable test machine available for lading damage evaluation, an attractive proposition for U.S. railroads.

TEST OBJECTIVES AND METHODOLOGY - ENDURANCE CAPABILITY OF THE VTU

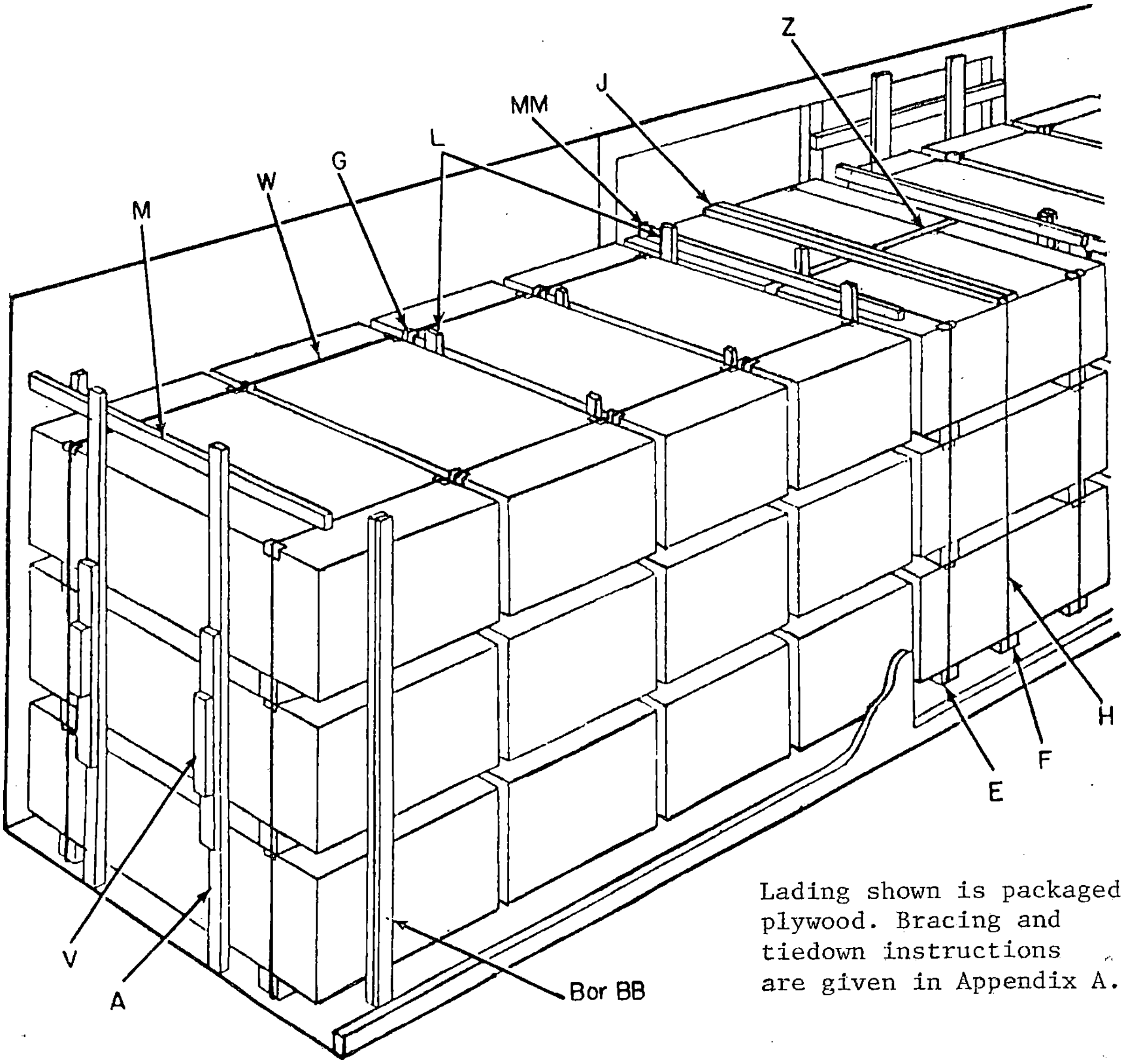
Since the VTU has never been used for long periods of time under continuous excitation conditions, an endurance test was proposed (in addition to the Input Validation Tests) to demonstrate the VTU's ability to replicate actual track conditions for sustained periods of time. Analysis of endurance data would then provide recommendations for better shipping techniques and predict derailment and lading damage conditions. A typical endurance cycle consisted of a three hour continuous excitation of the test vehicle on the VTU.

A 70-ton boxcar loaded with plywood was used as the test vehicle for the endurance testing. The configuration of plywood, as loaded in the car, is shown in Figure 36. The descriptive guidelines for the loading configuration of centered packaged plywood are presented in Appendix A. The test vehicle and lading were instrumented using accelerometers, string pots and a roll gyro. The data acquisition system made use of telemetry techniques as described in the previous section of this report, viz., "Validation of Track Geometry Input to the VTU".

For the VTU endurance test, data was acquired using the LTHD accelerometers. The Facility for Accelerated Service Testing (FAST) loop along with the Train Dynamics Track (TDT) and a portion of the Railroad Test Track (RTT) at the Transportation Test Center were selected as the sources of track geometry input for the endurance cycle.

Data from LTHD accelerometers was acquired at two different speeds (15 and 30 mph) on the above track section. The reformatted LTHD input was compiled to create a one hour digital tape comprised of runs at 15, 30 and 40 mph. The 40 mph run was scaled up from the 15 mph data. The above tape was repeated three times to constitute the three hour endurance cycle requirements.

To provide a more realistic input, a longitudinal actuator was connected to one of the couplers of the test vehicle and operated periodically to simulate buff and draft conditions. The longitudinal actuator input consisted of one cycle of a 1/2 Hz sinusoidal waveform, with an approximate stroke of six inches, at ten second intervals.



Lading shown is packaged plywood. Bracing and tiedown instructions are given in Appendix A.

FIGURE 36. LADING CONFIGURATION FOR ENDURANCE CAPABILITY TESTS OF VTU.

DATA ANALYSIS

The analysis of the VTU endurance test data consisted of obtaining PSD plots of selected channels for three different lading conditions. The channels selected for analysis were (Figure 6):

A5Z - Lading Vertical Accelerometer (*BR top corner)
A6X - Lading Lateral Accelerometer (BR top corner)
A11Z - Carbody Vertical Accelerometer (BR bottom sill)
A12X - Carbody Lateral Accelerometer (BR bottom sill)
A17X - Carbody Lateral Accelerometer (BR top sill)

* BR = "B" end of car, right side

During the course of endurance testing, data was acquired with the lading in three different positions: centered, shifted and recentered. Data analysis was only performed on the 30 mph runs of each endurance cycle.

The real-time strip chart responses and peak detection techniques were utilized to correlate the same time slices from the 30 mph runs of different lading conditions. These time slices were used for comparative analysis.

Figures 37 through 41 are PSD plots comparing the spectral and amplitude content of lading and carbody responses for centered and shifted lading conditions. It was observed that the lading was resting against the BR sidewall of the car after the first endurance cycle. This position of the lading was considered to be the shifted configuration of the lading and the endurance cycle was repeated. The reduced response of the lading in the shifted position was caused by its contact with the sidewall. This phenomenon is reflected in the PSD plots comparing the centered and shifted lading test runs. The power content of the centered lading response is seen to be higher than that of shifted lading.

The last endurance run on the VTU was conducted after the lading was recentered. The recentering of the lading was achieved by superelevating the car by 3 inches, coupled with a sinusoidal excitation of vertical actuators with a frequency sweep between 6 and 9 Hz. This frequency range was selected in order to excite the vertical lading resonance to facilitate easy centering of the lading. Figures 42 through 46 compare the lading and carbody responses for centered and recentered lading conditions. As can be seen, a good correlation exists between the two responses for all channels. The above results demonstrate that, at least for plywood, repositioning of the displaced lading can be achieved on the VTU during a prolonged test without having to reshift the lading manually. Future testing on the VTU could combine the use of sinusoidal excitation and paper air bags for easy and accurate repositioning of the lading. The air bags would be inserted between the lading and sidewalls of the car and inflated. The good comparison between the responses as seen in Figures 42 through 46 also demonstrates the VTU's performance in terms of repeatability.

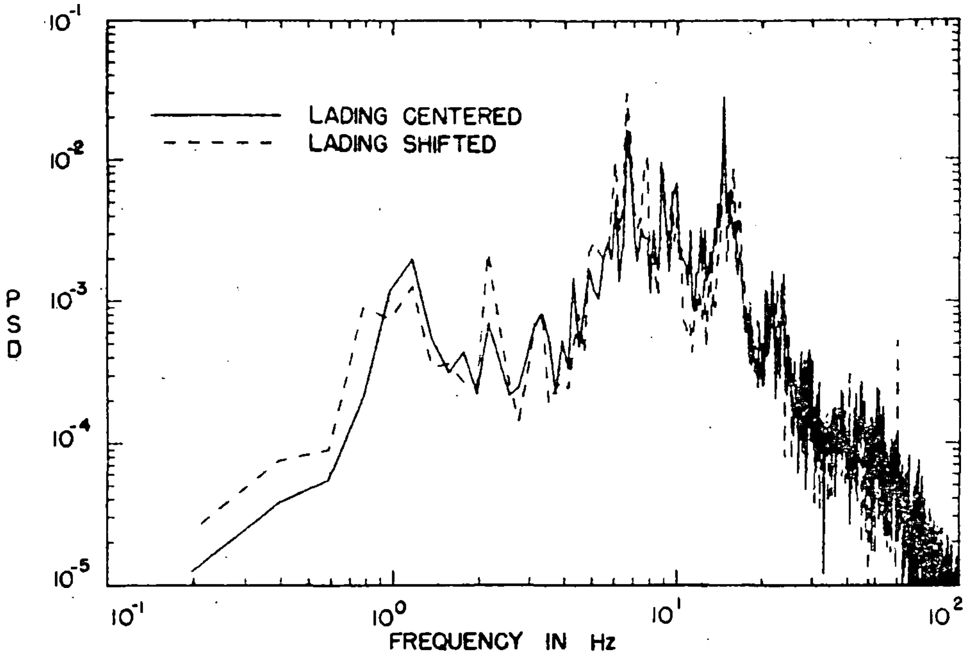


FIGURE 37. COMPARISON OF A5Z DURING ENDURANCE TEST, LADING (VERTICAL) RESPONSE.

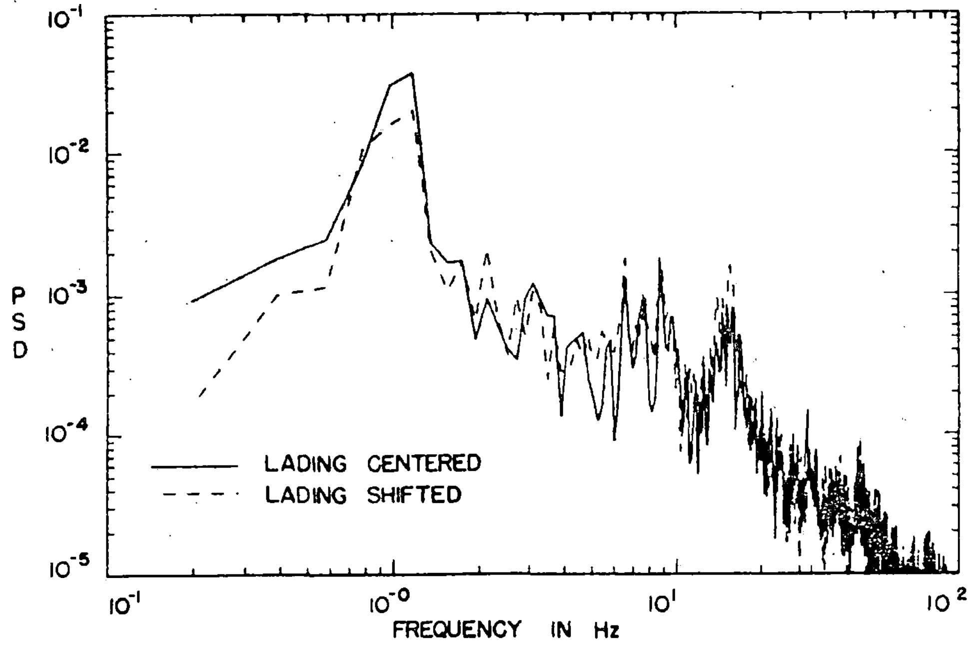


FIGURE 38. COMPARISON OF A6X DURING ENDURANCE TEST, LADING (LATERAL) RESPONSE.

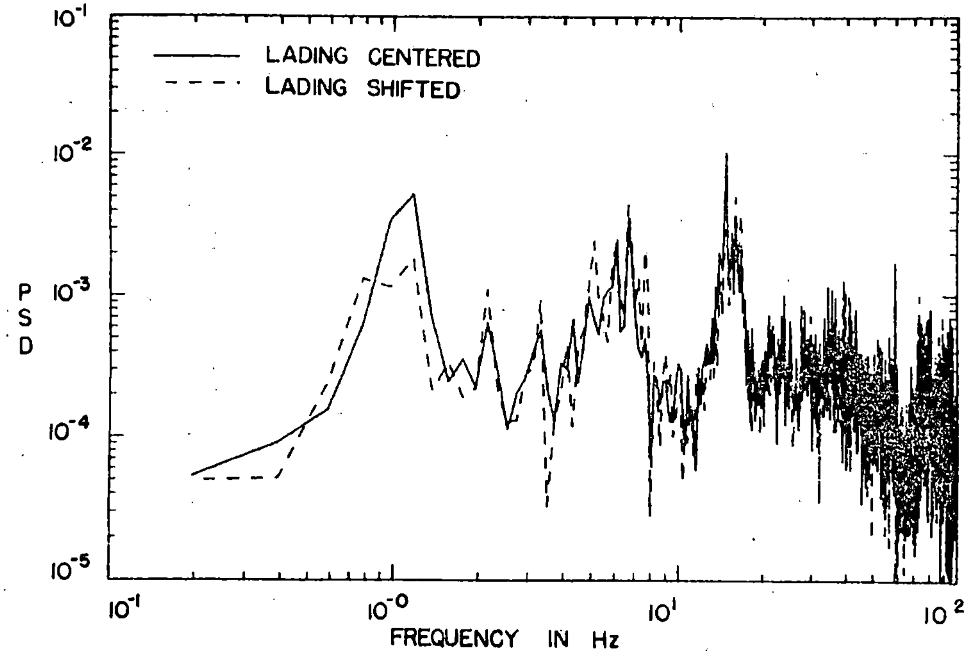


FIGURE 39. COMPARISON OF A11Z DURING ENDURANCE TEST, CARBODY BOTTOM SILL (VERTICAL) RESPONSE.

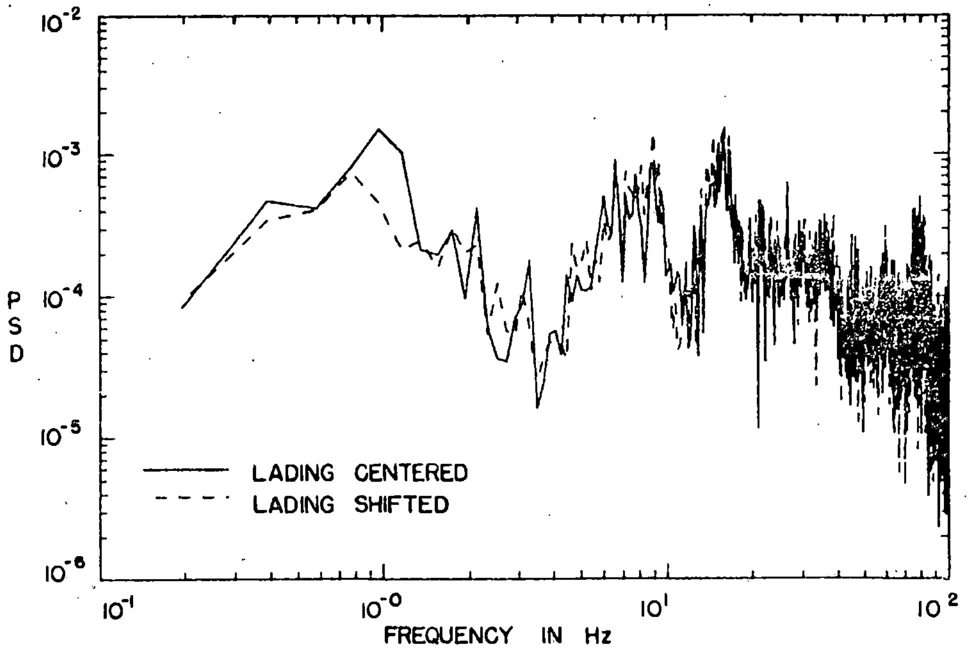


FIGURE 40. COMPARISON OF A12X DURING ENDURANCE TEST, CARBODY BOTTOM SILL (LATERAL) RESPONSE.

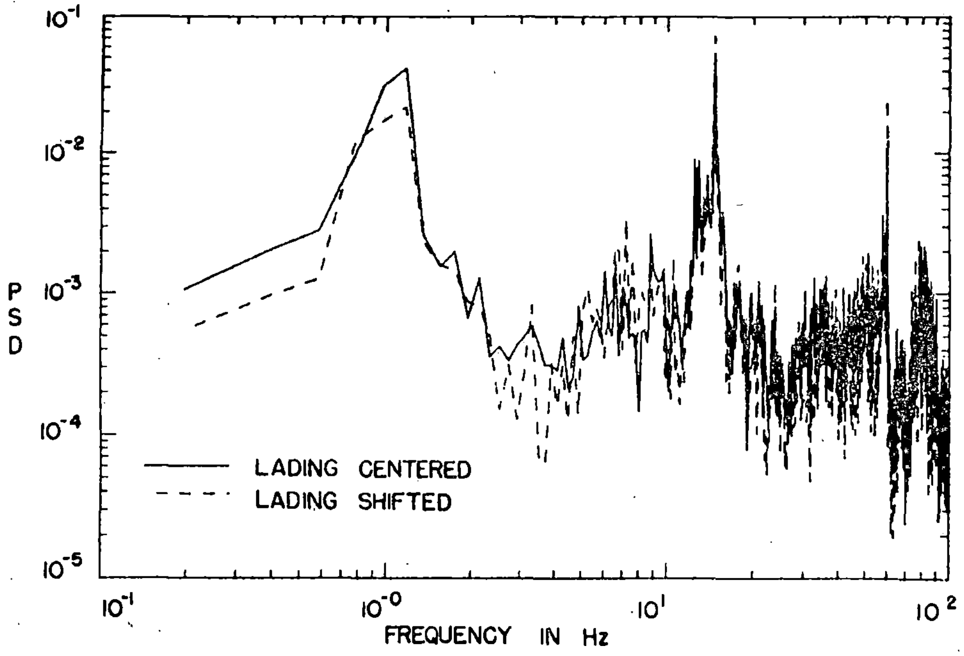


FIGURE 41. COMPARISON OF A17X DURING ENDURANCE TEST. CARBODY TOP SILL (LATERAL) RESPONSE.

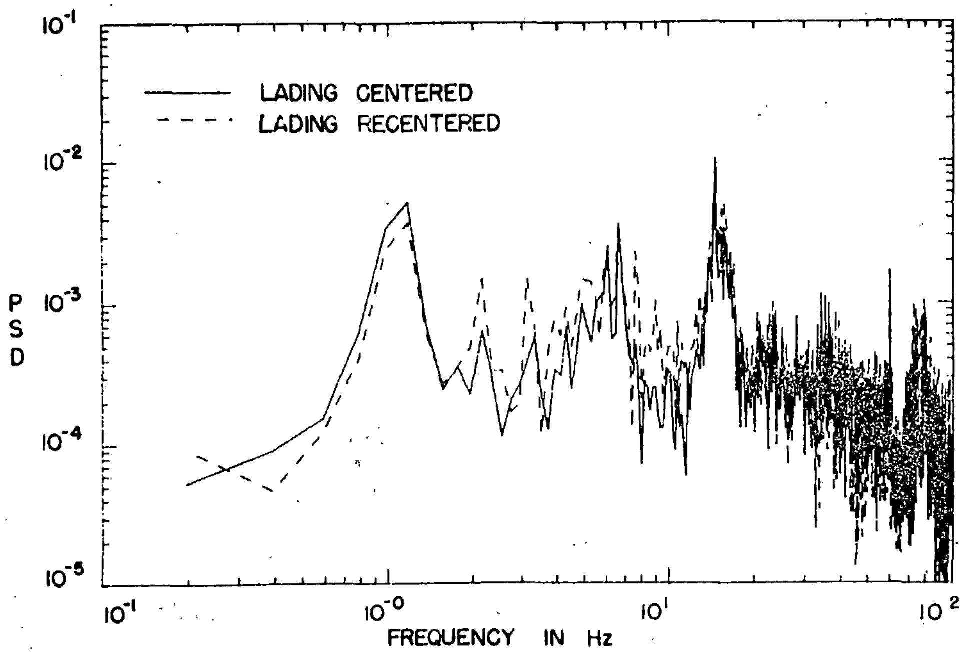


FIGURE 42. COMPARISON OF A11Z DURING ENDURANCE TEST, CARBODY BOTTOM SILL (VERTICAL) RESPONSE.

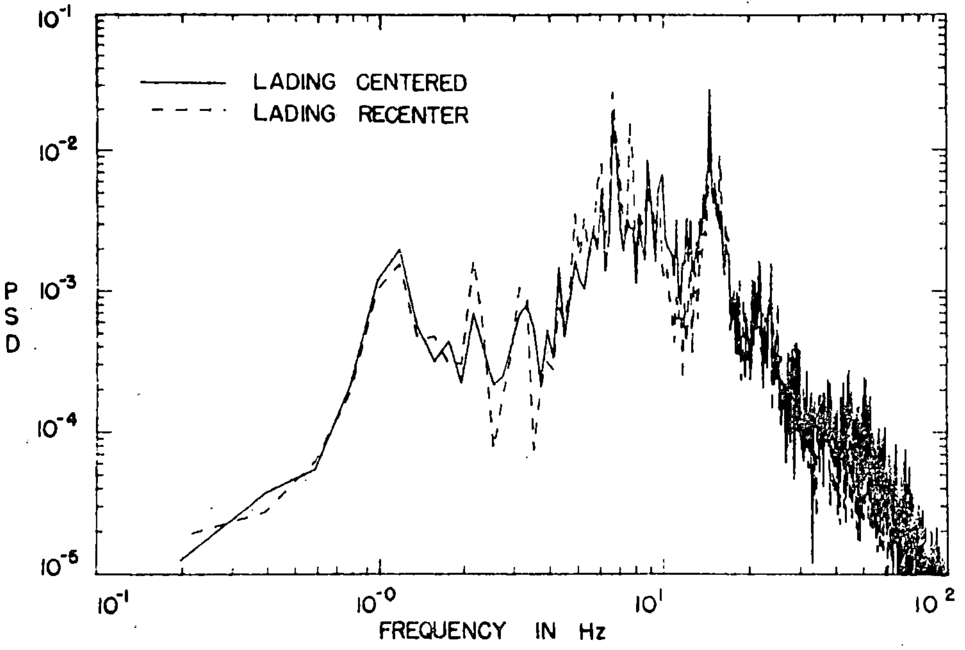


FIGURE 43. COMPARISON OF A5Z DURING ENDURANCE TEST, LADING (VERTICAL) RESPONSE.

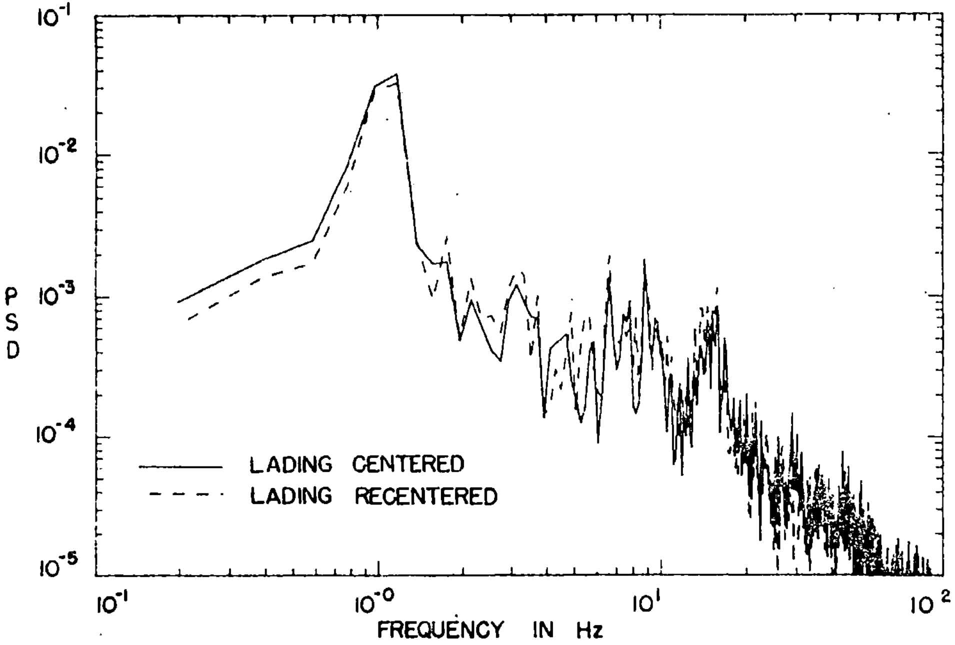


FIGURE 44. COMPARISON OF A6X DURING ENDURANCE TEST, LADING (LATERAL) RESPONSE.

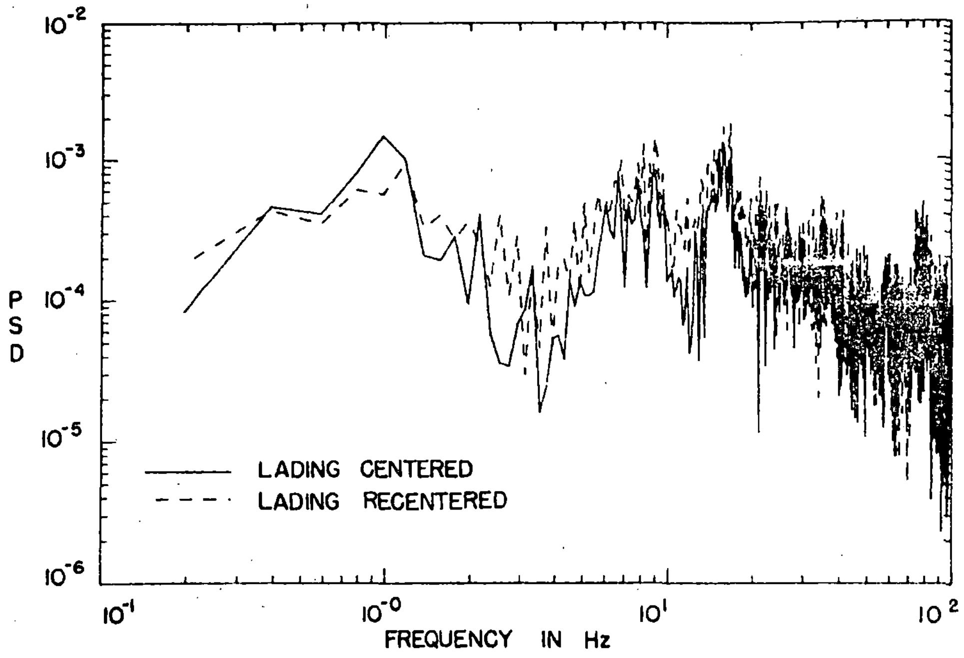


FIGURE 45. COMPARISON OF A12X DURING ENDURANCE TEST, CARBODY BOTTOM SILL (LATERAL) RESPONSE.

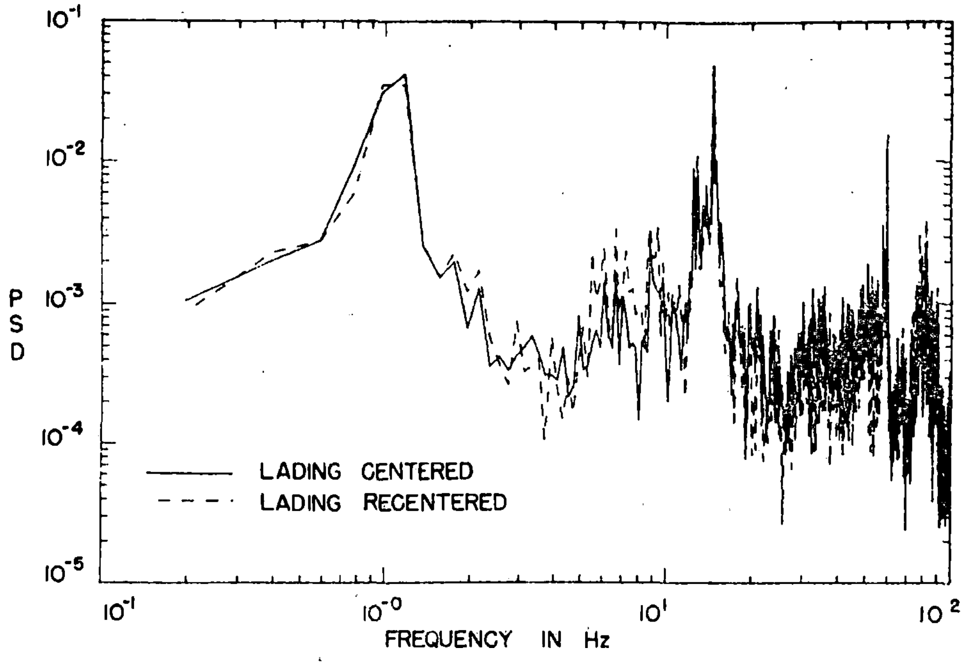


FIGURE 46. COMPARISON OF A17X DURING ENDURANCE TEST, CARBODY TOP SILL (LATERAL) RESPONSE.

The VTU input validation tests, described in the previous section of this report, compared track responses with the responses of the VTU tests using reformatted LTHD and Plasser data as inputs. The track used for the comparison was a well defined track section with known perturbations. Comparing responses from the FAST track runs and the VTU endurance runs could be used to provide validation over a section of track more representative of actual in-service conditions. Figures 47 through 50 are PSD overlays of Channels A11Z, A12X, A5Z and A6X for the track and VTU endurance runs. These PSD plots are from the same time slice of the 30 mph runs. The overall frequency contents of the track and VTU runs compare very well. The amplitudes of the channels differ slightly. The reason for this could be associated with the fact that the track runs used canned dog food in the stretch wrap configuration as lading, whereas packaged plywood was used in the case of the VTU endurance runs. The close similarity between the responses from the track (FAST loop) and the VTU endurance runs further reiterates the use of LTHD reformatted space curves as a viable form of track geometry input to the VTU.

CONCLUSIONS OF VTU'S ENDURANCE CAPABILITY TESTS

The VTU is a unique facility, which has proven itself useful in evaluating the effects of prolonged track geometry inputs to a test vehicle in terms of carbody and lading response. Any prescribed profile of the track used in revenue service, measured using suitable techniques, can be reformatted and used as input for the VTU under controlled conditions. Detailed analysis of lading and carbody responses can be carried out to investigate in-service conditions.

IMPACT TESTING

A complete lading damage evaluation program under controlled conditions should include: a) a realistic track geometry input, b) capability to simulate the input for prolonged periods of time, and c) in-service yard impacts.

In order to fulfill the requirements of a complete lading damage evaluation, impact tests were carried out at the TTC on a suitable TTC track. This impact testing was designed to simulate in-service yard conditions experienced by a freight car and measure their effects on lading.

The test vehicle was pushed by a locomotive at the selected test speeds and was allowed to impact freely against a stationary locomotive. Test runs were made at 4, 5 and 6 mph with the test vehicle impacted in both directions.

Two sets of impact tests were conducted along with the VTU endurance cycles. The data acquired during impact testing was comprised of the responses of the lading and carbody accelerometers. Initial test runs were made without filtering any of the responses, and for subsequent runs data was filtered with a 30 Hz low pass filter. In all the impact test runs, the test car was the moving car (usually referred to as the hammer car). One locomotive was used as an anvil or standing car during the first section of impact test runs while two locomotives were used as standing cars during the second set of runs. The AAR impacting procedure calls for five (5) empty cars (250-300 kips), with air brakes set, as the anvil cars. As the objective of the endurance tests was to

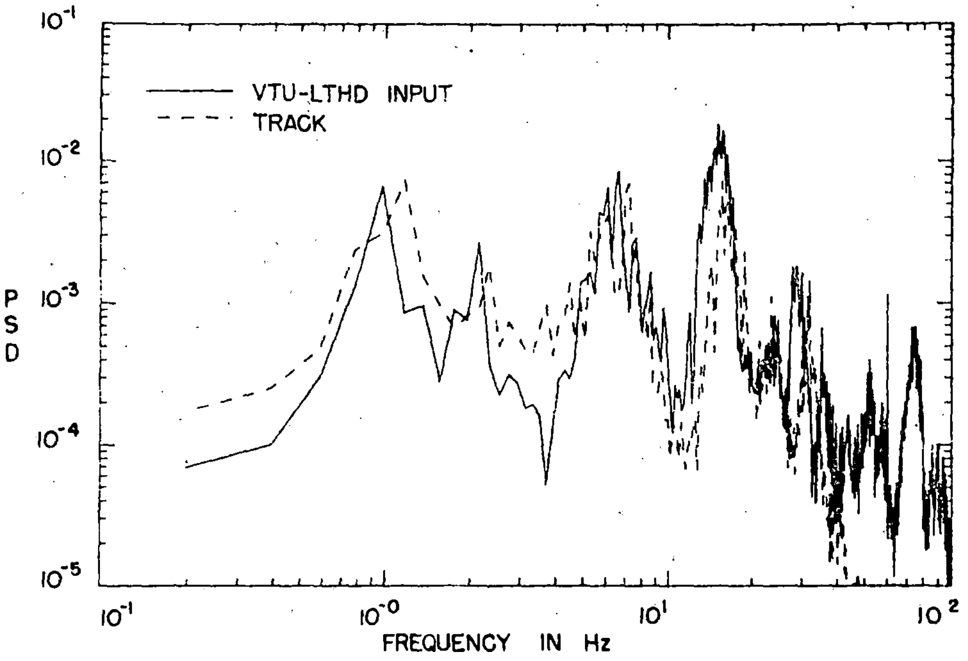


FIGURE 47. COMPARISON OF A11Z FOR THE FAST TRACK AND VTU ENDURANCE RUNS, CARBODY BOTTOM SILL (VERTICAL) RESPONSE.

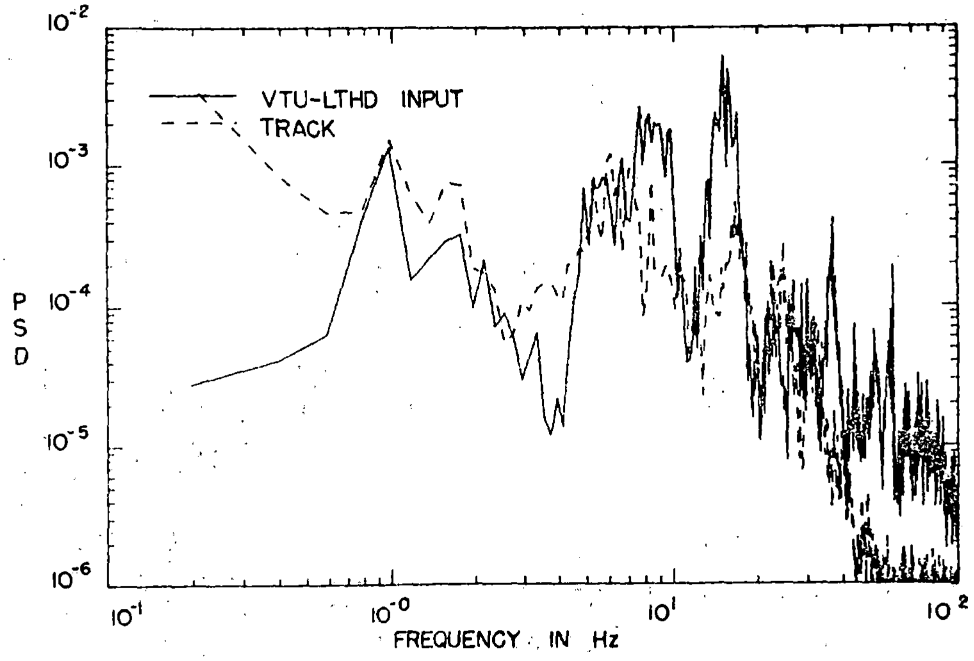


FIGURE 48. COMPARISON OF A12X FOR THE FAST TRACK AND VTU ENDURANCE RUNS, CARBODY BOTTOM SILL (LATERAL) RESPONSE.

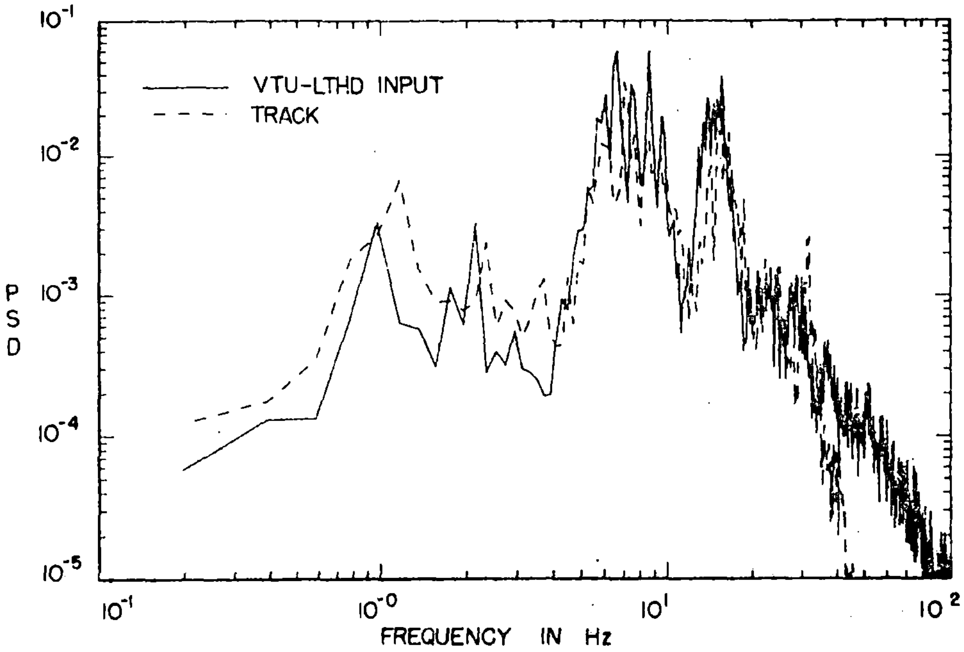


FIGURE 49. COMPARISON OF A5Z FOR THE FAST TRACK AND VTU ENDURANCE RUNS, LADING (VERTICAL) RESPONSE.

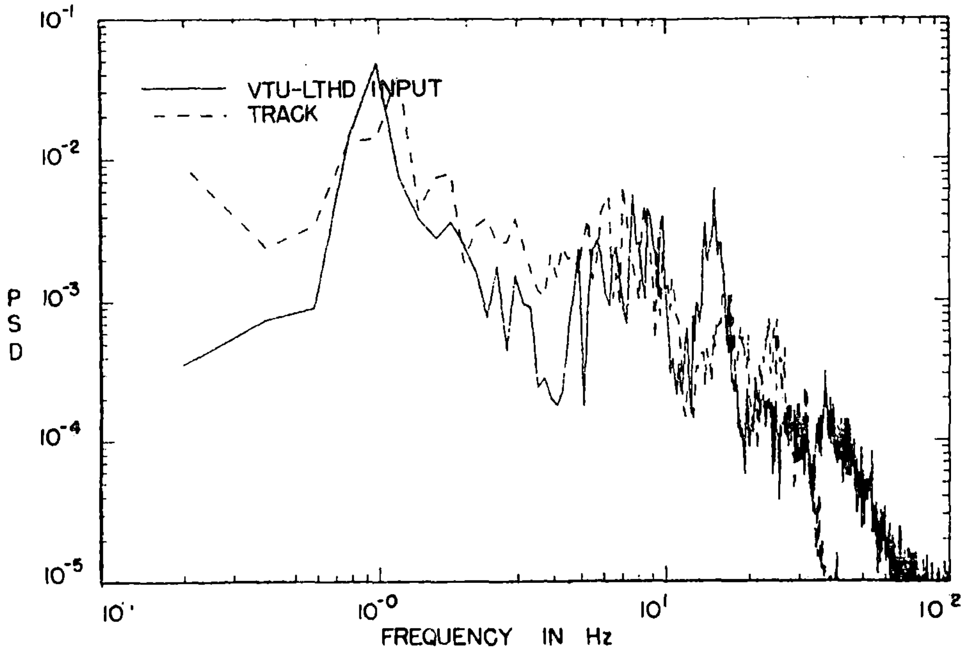


FIGURE 50. COMPARISON OF A6X FOR THE FAST TRACK AND VTU ENDURANCE RUNS, LADING (LATERAL) RESPONSE.

demonstrate the RDL's capability to perform tests on the VTU, followed by impact tests on the track, the use of locomotives as anvil cars was proposed as an experimental expedient, to cut down the time and logistics involved.

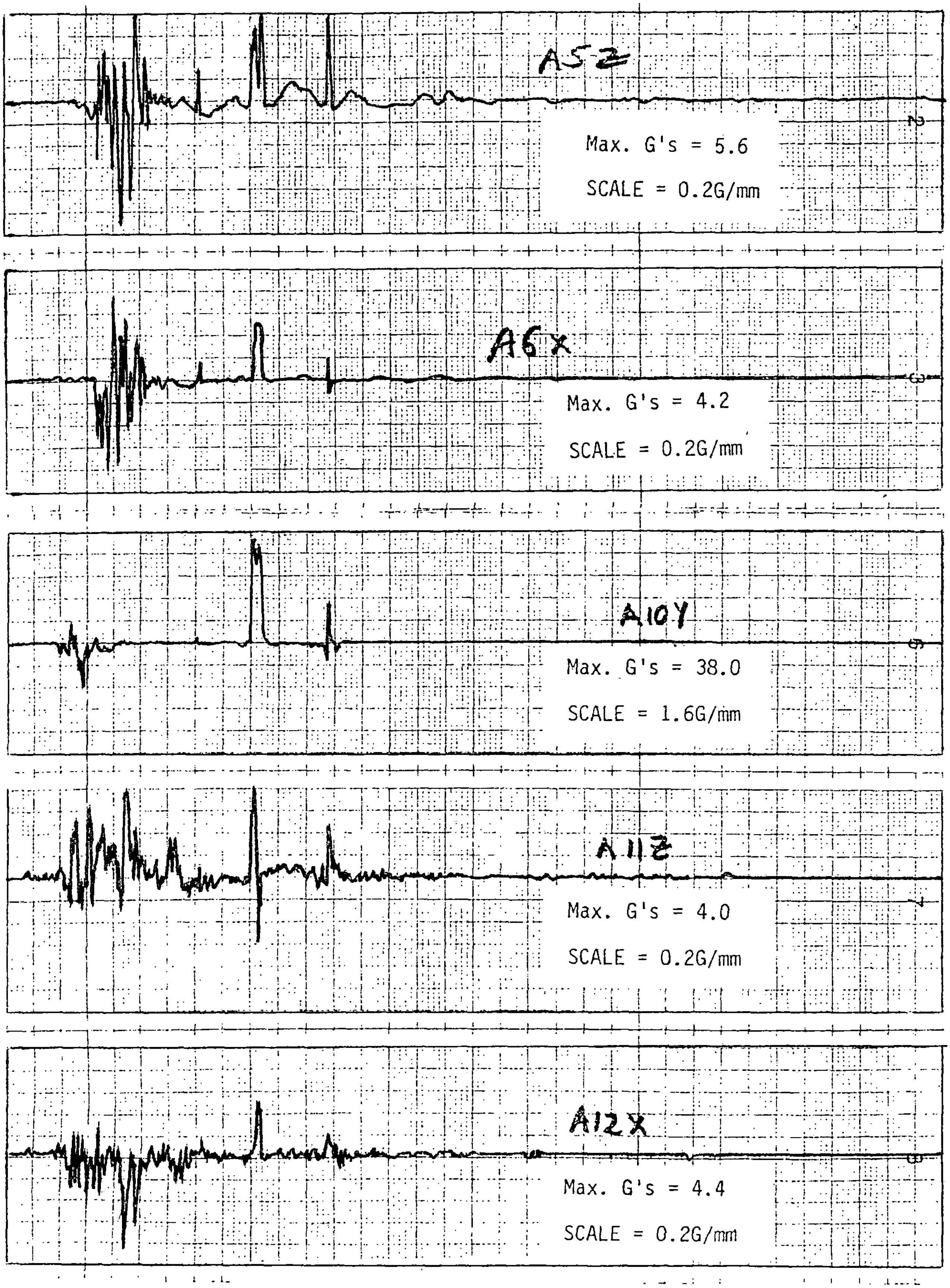
The impact data was acquired at the rate of 800 samples/second. The following data channels were recorded on real-time strip charts, in addition to digital acquisition of all test channels (Figure 6).

D1X - Lading Lateral Displacement (B-end)
A5Z - Lading Vertical Accelerometer (BR top corner)
A6X - Lading Lateral Accelerometer (BR top corner)
A8Z - Lading Vertical Accelerometer (*AR top corner)
A9X - Lading Lateral Accelerometer (AR top corner)
A10Y - Carbody Longitudinal Accelerometer (B-end)
A11Z - Carbody Vertical Accelerometer (BR bottom sill)
A17X - Carbody Lateral Accelerometer (BR top sill)
* AR = "A" end of car, right side.

Figures 51 and 52 are representative time history strip chart records of selected data channels for the impact tests conducted at 6 mph. Figure 51 represents unfiltered data, while Figure 52 is the data, low pass filtered at 30 Hz.

CONCLUSIONS OF IMPACT TESTING

Impact tests were successfully carried out on a selected TTC track in conjunction with the VTU endurance tests. This series of tests confirms the capability of TTC to conduct a complete lading damage evaluation program under controlled conditions.



Strip Chart Speed = 100 mm/sec

FIGURE 51. REPRESENTATIVE REAL-TIME RESPONSES (UNFILTERED) FROM 6 MPH IMPACT TESTS.

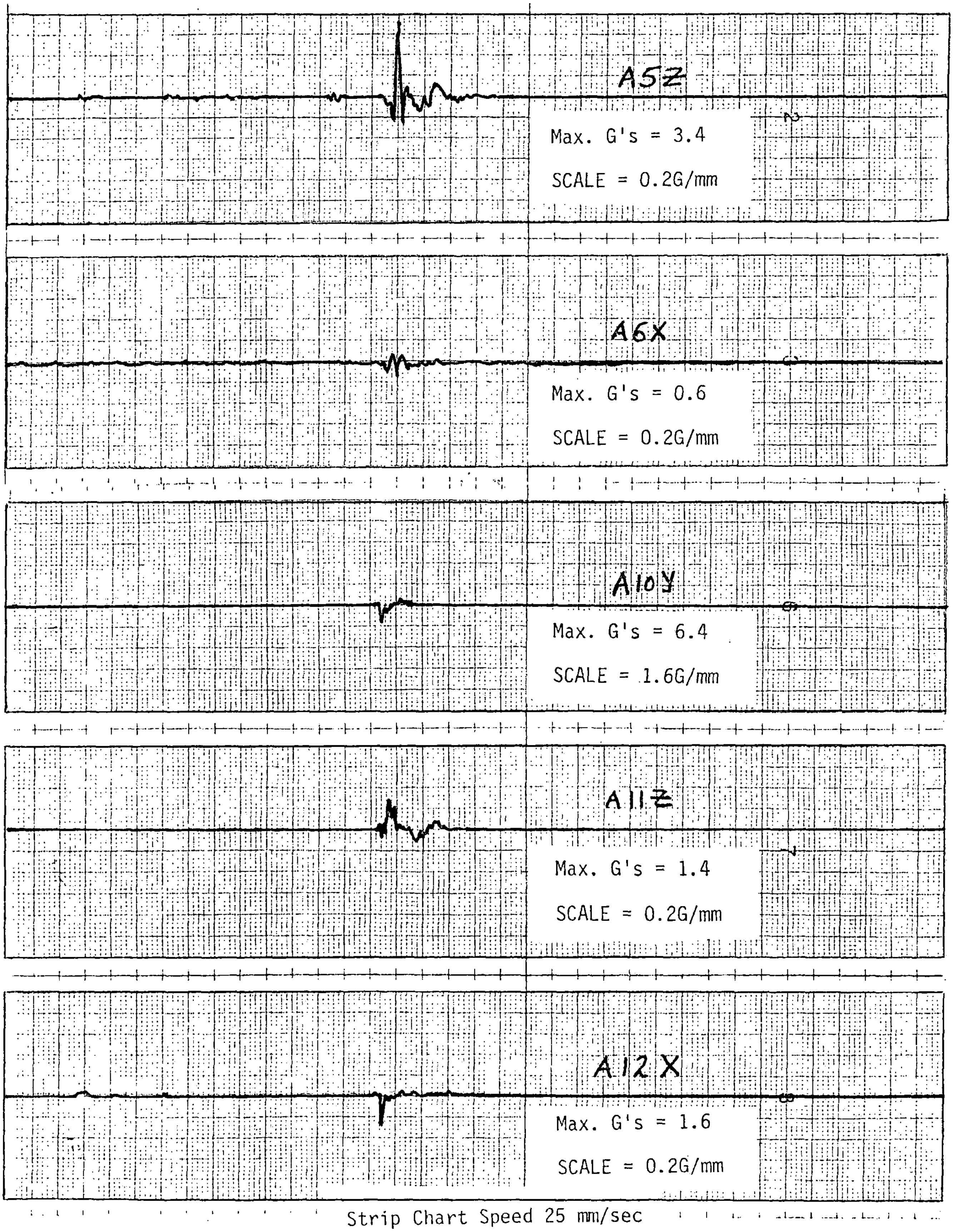


FIGURE 52. REPRESENTATIVE REAL-TIME RESPONSES (30 Hz LOW PASS FILTERED) FROM 6 MPH IMPACT TESTS.

REFERENCES

1. Cohen, A. and W. A. Hutchens, "Methods for Reconstruction of Rail Geometry from Mid-Chord Offset Data," The ASME Joint Transportation Engineering Conference, Chicago, Illinois, October 11-14, 1970.

2. Rajkumar, B. R., F. D. Irani and C. L. Orth, "Replication of Revenue Track Input Using a Vibration Test Unit for Freight Car Structure and Lading Damage Evaluation," Journal of Engineering for Industry, Vol. 106, February, 1984.

3. Corbin, J., J. Lazzaro and C. Peterson, "Locomotive Track Hazard Detector Program (LTHD)," Report No. FRA/ORD-82/26, June, 1982.

4. Corbin, J., (The MITRE Corporation), "Noise Associated with the Reformatted Plasser Space Curves as VTU Input," Letter to F. D. Irani, March 25, 1982.

APPENDIX A

CENTERED LOAD WITH PACKAGED PLYWOOD

ITEM	DESCRIPTION (REFER TO FIGURE A-1)
A) End Wall Fillers	Minimum of two verticals 2" to 6" thick x at least 4" wide lumber, each spaced 18" from each side wall and nailed to end walls. Extend verticals from the floor of the car to a height of 6" above the top of the load to ensure that plywood cannot contact end walls.
B) First Stack Side Wall Protection or Alternate BB	Two laminated 2" x 4" lumber or equivalent applied 12" from end of car and nailed to side wall. Backup fillers (BB) may be short pieces if combined length equals fifty per cent of full height 2" x 4". Not required when Item A is 6" thick when measured from the junction of the floor and the end wall.
C) Side Wall Furring Strips (Not required in steel wall cars)	Minimum 3/8" x 4" verticals.
E) Risers	Minimum 2" x 4" material or laminated equivalent. Secured to package with strapping or placed loose on floor and between packages. Nailing to floor optional.
F) Doorway Stabilizer	2" x 4" lumber placed over unitizing strap (Item H), and nailed to floor of car with a minimum of six 16d nails - when using an air hammer. If nails are hand-driven, minimum of five 20d nails.
FF) Doorway Guide Rails	As an alternate, when nailing of Item F is omitted, apply a minimum of one 2" x 4" x 7' lumber placed lengthwise adjacent to bottom bundle on each side, secured by railing to floor of car with a minimum of six 16d nails. If risers (Item E) are not secured to packages by the package straps, use guide rails consisting of two pieces of 2" x 4" x 7' lumber laminated.
G) Corner Protectors (Optional)	Type and size in accordance with manufacturer's specifications for strapping tension applied. Corner protectors are used to distribute pressure over a large area and thus minimize indentation markings of steel strapping used in packaging. Use is at the option of the shipper. Any exceptions to the lading as a result of these indentations, due to lack of corner protection, will not be considered rail carrier responsibility.

ITEM	DESCRIPTION (REFER TO FIGURE A-1)
H) Unitizing Steel Strap	Encircling doorway area lading. One 1¼" x .035" or equivalent steel strap having joint strength of 3400 pounds or more, locate under doorway stabilizer (Item F), if used.
J) Hold Down	One piece of 2" x 4" lumber placed crosswise or corner protectors under steel strap (Item H) across top of doorway area bundles.
K) Doorway Void Blocking	Minimum of two one piece 2" x 4" verticals extending from floor to 4" above top of load. Maximum of two pieces of 2" x 4" lumber laminated to be used for any one vertical member.
L) Separators (Vertical) (As Required)	Minimum of two 1" x 4" lumber extending from floor to above top of load. Maximum of two 2" x 4" lumber laminated to be used for any one separator. Use as required to eliminate lengthwise void. Apply between crosswise stacks in ends of car and/or between lengthwise and crosswise stacks. Item MM is placed crosswise of car. Item L to be nailed to plywood lifts if Item MM is not used. Full sheets of plywood or other adequate protection required if lading is machine edged plywood.
M) Crossbrace	Minimum of one 1" x 4" lumber secured to each Item A with three 16d nails. To be used when Item A is not securely nailed to end wall.
MM) Crossbrace	Minimum of one 1" x 4" lumber secured to each Item L with three 16d nails. Not necessary when Item L nailed to plywood lifts.
N) Crossbrace	Minimum of one 2" x 4" nailed to Item K with three 16d nails. Not necessary when Item K nailed to plywood lifts.
V) Backup Fillers	When end walls are bowed, fill the void between filler and end walls with short pieces of lumber, securely nailed in place.
W) Package Straps	Steel straps average tensile strength of 1440 pounds (5/8" x .020" or equivalent).
Z) Vertical Stabilizer	Apply between rows of lengthwise lifts. Minimum of two 2" x 4" between each stack extending from floor of car to above top of load.

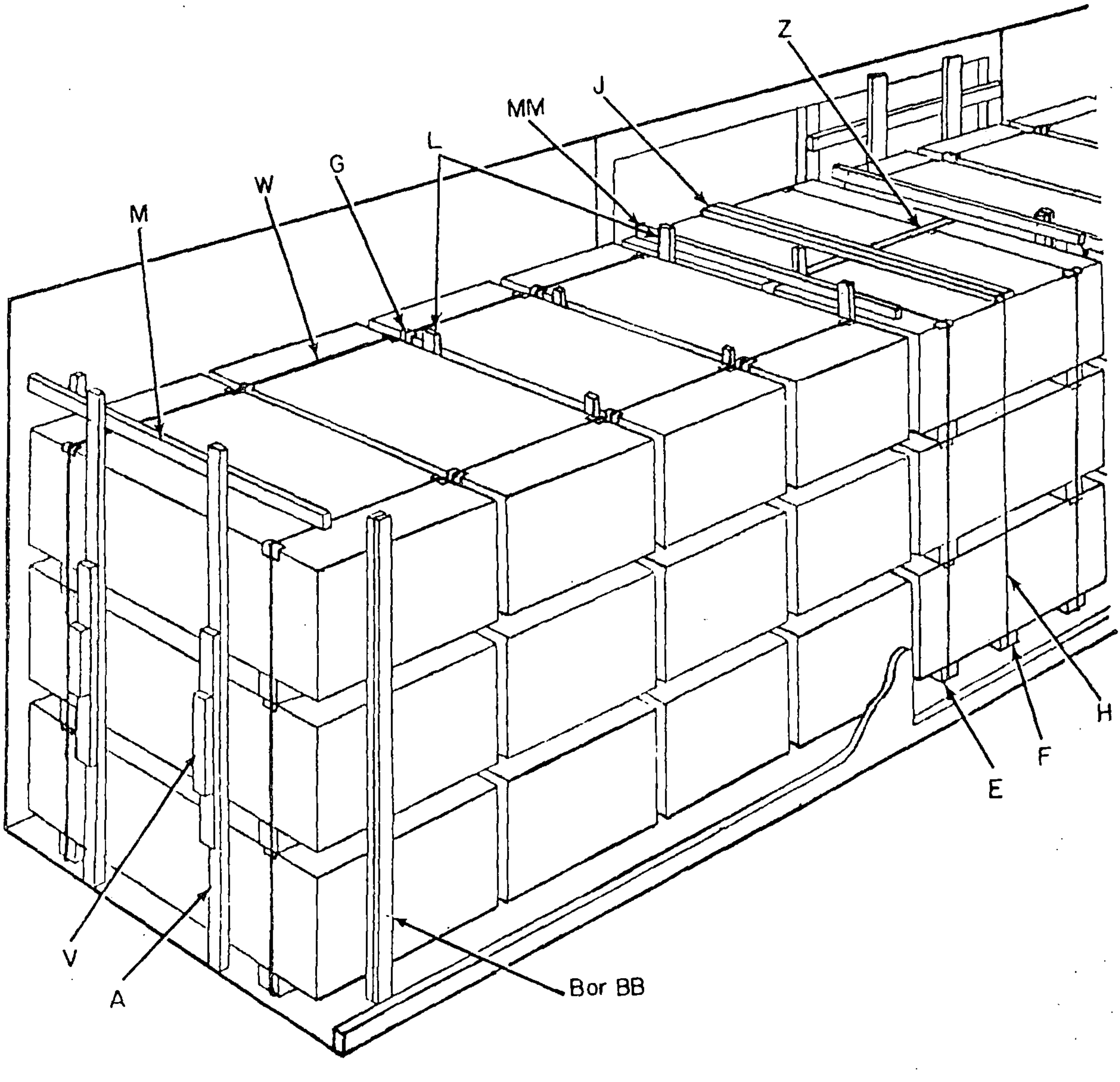


FIGURE A-1

Validation of Track Geometry Input to the Vibration Test Unit (VTU) and the Endurance Capability of the VTU, B.R. Rajkumar and F.D. Irani, 1984
02-Track-Train Dynamics