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PASSENGER RIDE QUALITY OF A SPAN BOLSTER CAR WITH FREIGHT TRUCKS

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16. Abstract

A test was performed to measure the ride quality of an eight axle Span Bolster Rail Car with freight trucks. The Federal Railroad Administration (FRA) and the Association of American Railroads (AAR), felt it necessary to examine the use of freight trucks and Span Bolsters on passenger cars because, the Peacekeeper Rial Garrison cars, which were to carry people, were designed for the use of Span Bolsters and freight trucks.

Vibration levels were measured on a DUPX 29769 Span Bolster Tank Car and the ASFX 1965 Passenger Car. The test was performed while the tank car was in revenue service from Beaumont, Texas, to Charleston, South Carolina, and back over two railroad lines. Vibration levels were compared to ISO specifications for personal ride quality with respect to the fatigue and decreased proficiency limits. It was found that the combination of Span Bolster and freight trucks produced a higher level of vibration than that of a passenger car, which corresponded to a low allowable exposure limit as dictated by the fatigue and decreased proficiency limit. This meant that personnel will fatigue in a usual eight hour shift.

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1.0 INTRODUCTION

Ride quality for passengers as well as equipment is an important factor in the railroad industry. Ride quality, which is a measure of the vibration level relative to a person can be affected by the first six rigid body modes of vibration and possibly the first flexible body modes:

1. Bounce
2. Lower Roll
3. Upper Roll
4. Pitch
5. Yaw
6. Longitudinal
7. Bending

Usually the longitudinal mode is disregarded, but it is a factor in this case.

Passengers can become uncomfortable, nauseous, or even incapacitated because of poor ride quality. High vibration levels can also cause equipment failure.

Several of the Peacekeeper Rail Garrison (PRG) cars ride on two span bolsters, with each span bolster supported by two standard three piece freight trucks. A limited amount of span bolster cars are in existence today. The combination of freight trucks and span bolsters raises many questions regarding the ride quality for passengers and electronic equipment. In order to determine the ride quality of a car equipped with span bolsters and freight trucks, a test was conducted by the Association of American Railroads (AAR), Transportation Test Center (TTC), using a span bolster tank car (DUPX 29769), which is similar to the PRG cars in size and weight. The tank car was tested during regular operation between Beaumont, Texas, and Charleston, South Carolina. Vibration data for ride quality was obtained for both the loaded and empty tank car conditions. Vibration data was also collected on a passenger car in the same consist for comparison. Track geometry type data was collected with the Locomotive Track Hazard Detector (LTHD) system so a comparison to track class could be made.

2.0 OBJECTIVES

The major objective of the test was to better understand the ride quality of a car equipped with span bolsters and freight trucks. The following information was used in obtaining that objective.

1. The ride quality of the DUPX 29769 tank car measured per International Organization for Standardization (ISO) specifications and Advisory Publication #1/17A for Vibration Exposure Limits issued by the Air Standardization Coordinating Committee (ASCC)

2. The comparison of ride quality for the ASFX 1965 passenger car and the DUPX 29769 tank car

3.0 PROCEDURE

A tank car owned by DuPont (DUPX 29769) was tested while in revenue service from Beaumont, Texas, to Charleston, South Carolina. The tank car was coupled to a passenger car (ASFX 1965) via a buffer car. Vibration data was collected at the axle bearing adapter, truck, span bolster, and car body of the tank car. Accelerations on the passenger car were measured on the car body. A high lateral accelerometer was also used to measure the roll on both the tank car and passenger car. Accelerations were measured in the lateral and vertical directions at all locations. Longitudinal acceleration was measured at the span bolster of the tank car and the car bodies of both cars. All of the previous accelerations were filtered at a frequency of 30 Hz. In addition to the low frequency measurements above, eight high frequency measurements were collected. The high frequency accelerometers were mounted on the bearing adapter, span bolster, and car body of the tank car and filtered at a frequency of 2000 Hz. Including the speed and three channels for the LTHD track geometry system, 31 channels of data were collected. Figure 1 shows the configuration of the test cars and the measurement locations.

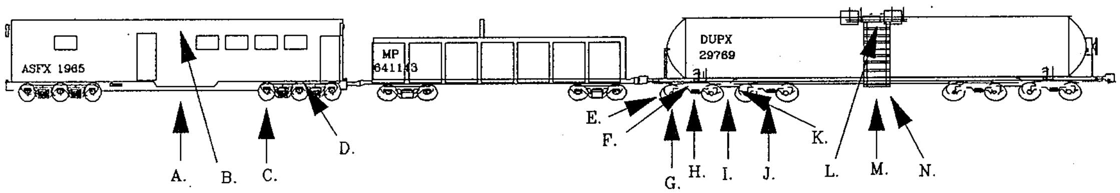


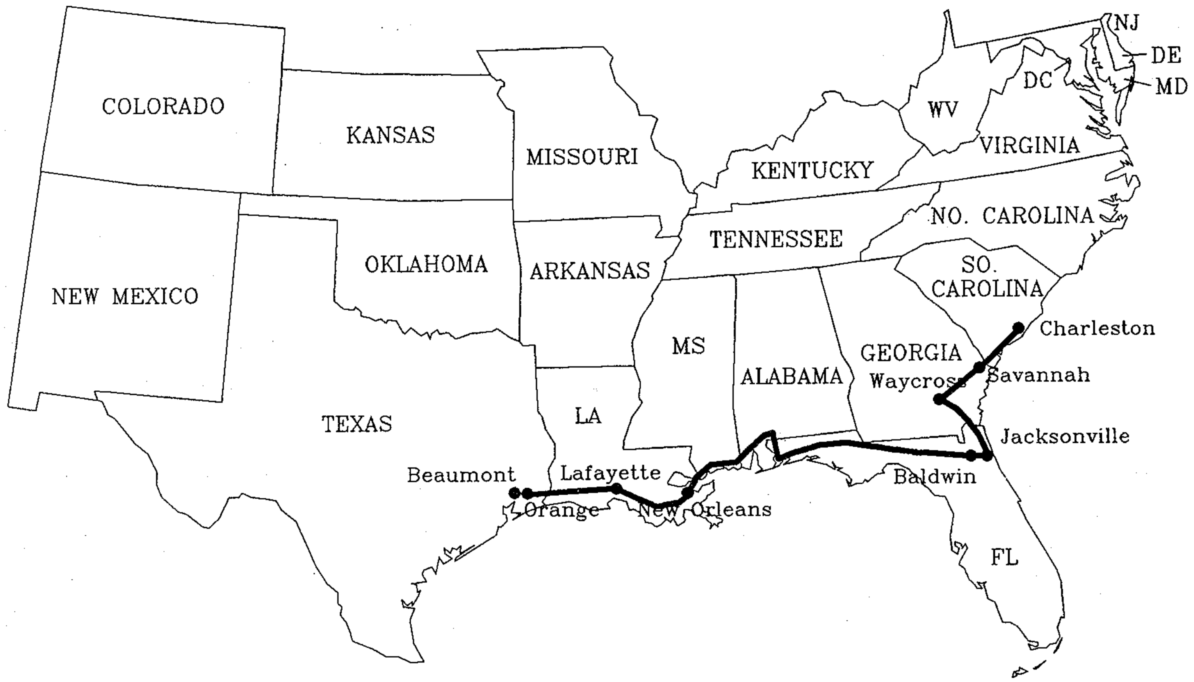
Figure 1. Test Setup and Transducer Locations

3.1 TEST PREPARATION

The first step in test preparation was to contact DuPont and ask permission to use one of their span bolster tank cars. The one condition upon which permission was granted was that the normal operation of the tank car was not to be affected. Therefore, it was necessary to perform the ride quality test while the tank car was in revenue service. Normal revenue service for the tank car meant shipping 43,000 gallons of ethylene glycol from Beaumont, Texas, to Charleston, South Carolina via two railroads, "A" and "B".

The grade A ethylene glycol was refined at the PD Glycol Plant in Beaumont, Texas. The glycol was then shipped by way of railroad to the DuPont Cooper River Plant in Charleston, South Carolina. The glycol was used at Cooper River in the manufacturing of polyester fibers and raw materials.

The next step in test preparation was to contact the aforementioned railroads. The shipping route was received from both railroads, with the interchange point being New Orleans, Louisiana (figure 2).



DAY	APPROX. TIME	ACTIVITY	APPROX. MILES
1	11:00 AM 8:00 PM	Move from DuPont to Orange Wait for "A" pick-up	
2	1:00 AM 7:00 AM 2:00 PM 8:00 PM	Pick-up "A" at Orange and depart Arrive at Lafayette Depart Lafayette Transfer to "B" in New Orleans	115 150
3	8:00 AM 5:00 PM	"B" pick-up Leave New Orleans	600
4	9:00 PM	Arrive at Baldwin	
5	2:00 PM 8:00 PM	Leave Baldwin Arrive Waycross	100
6	1:00 AM 2:30 PM	QUICK CONNECT - Leave Waycross on 492 Arrive Charleston	200

Figure 2. Normal Shipping Route for DuPont Ethylene Glycol

Time tables and any operating restrictions were requested from each railroad. Two major restrictions applied while on the "B" Railroad. The first restriction regarded the position of the passenger car in the freight train. Only 7,000 trailing tons were allowed to be pulled through the passenger car. This meant that at times the three car test consist would be in the middle or at the end of the train. The second restriction was in reference to the weight of the tank car. An empty car was required at each end of the tank car while passing over certain bridges. The MP 641143 low side gondola power car served as that buffer car.

The Federal Railroad Administration (FRA) track geometry exception reports were requested for the tank car route. They were supplied by ENSCO, Inc. and listed track class and other pertinent information.

The last step in test preparation was to arrange a Government Bill of Lading (GBL) for the entire route from TTC through Texas, to South Carolina, and back.

3.2 MEASUREMENT PREPARATION

Meetings were held between the FRA, TTC, Transportation Systems Center (TSC), and National Technical Systems (NTS) to determine measurements, transducers, and locations. Table 1 lists the measurements that were chosen.

Table 1. Ride Quality Test Measurements

NUMBER	TRANSDUCER	LOCATION AND TYPE OF MEASUREMENT
1	Accelerometer	ASF, car body, center line, center of car, vertical
2	Accelerometer	ASF, car body, center line, center of car, lateral
3	Accelerometer	ASF, car body, roll
* 4	Accelerometer	ASF, car body, center line, A-end, vertical
* 5	Accelerometer	ASF, car body, center line, A-end, lateral
* 6	Accelerometer	ASF, car body, center line, A-end, longitudinal
* 7	Accelerometer	DUPX, car body, center line, A-end, vertical
* 8	Accelerometer	DUPX, car body, center line, A-end, lateral
* 9	Accelerometer	DUPX, car body, center line, A-end, longitudinal
10	Accelerometer	DUPX, car body, center line, center of car, vertical
11	Accelerometer	DUPX, car body, center line, center of car, lateral
* 12	Accelerometer	DUPX, car body, roll
13	Servo Accel	LTHD DUPX, axle 1, right, vertical
14	Servo Accel	LTHD DUPX, axle 1, left, vertical
15	Servo Accel	LTHD DUPX, axle 1, left, lateral
16	Accelerometer	DUPX, leading truck bolster, center, vertical
17	Accelerometer	DUPX, leading truck bolster, center, lateral
18	Accelerometer	DUPX, span bolster, center, vertical
19	Accelerometer	DUPX, span bolster, center, lateral
20	Accelerometer	DUPX, span bolster, center, longitudinal
21	Accelerometer	DUPX, trailing truck bolster, center, vertical
22	Accelerometer	DUPX, trailing truck bolster, center, lateral
* 23	Tachometer	ASF, center axle, left, speed
* 24	+ PE Accel	DUPX, span bolster, center, vertical
* 25	PE Accel	DUPX, span bolster, center, lateral
* 26	PE Accel	DUPX, span bolster, center, longitudinal
* 27	PE Accel	DUPX, car body, center line, center of car, vertical
* 28	PE Accel	DUPX, car body, center line, center of car, lateral
* 29	PE Accel	DUPX, axle 1, right, vertical
* 30	PE Accel	DUPX, axle 1, left, vertical
* 31	PE Accel	DUPX, axle 1, left, lateral

* Channel displayed real-time on a strip chart.
\+ Piezoelectric Accelerometers

The six channels on the passenger car (1,2,3,4,5,6) were located to give the six modes of vibration for passenger ride quality (section 1.0). The speed channel (23) was located on the passenger car simply for convenience. Four channels (4,5,6,23) were recorded as real-time on a strip chart.

Six channels on the tank car (7,8,9,10,11,12) were located to give the six modes of vibration for passenger ride quality. Three channels were used for the LTHD system (13,14,15) to record track input. Eight channels were also used to measure high frequency shock and vibration on the tank car (24,25,26,27,28,29,30,31). Four channels (7,8,9,12) and all of the high frequency channels (24-31) were recorded as real-time on strip charts.

3.3 TRANSDUCER INSTALLATION

All transducers, with the exception of the tachometer, were installed at the PD Glycol plant in Texas. The tachometer was installed on the passenger car at TTC.

3.3.1 Passenger Car Ride Quality Transducers

Transducers 1 and 2 were installed in the center of the floor of the passenger car (figure 3). The accelerometers were mounted to an aluminum angle bracket. The aluminum was then mounted the floor of the ASF car with screws.

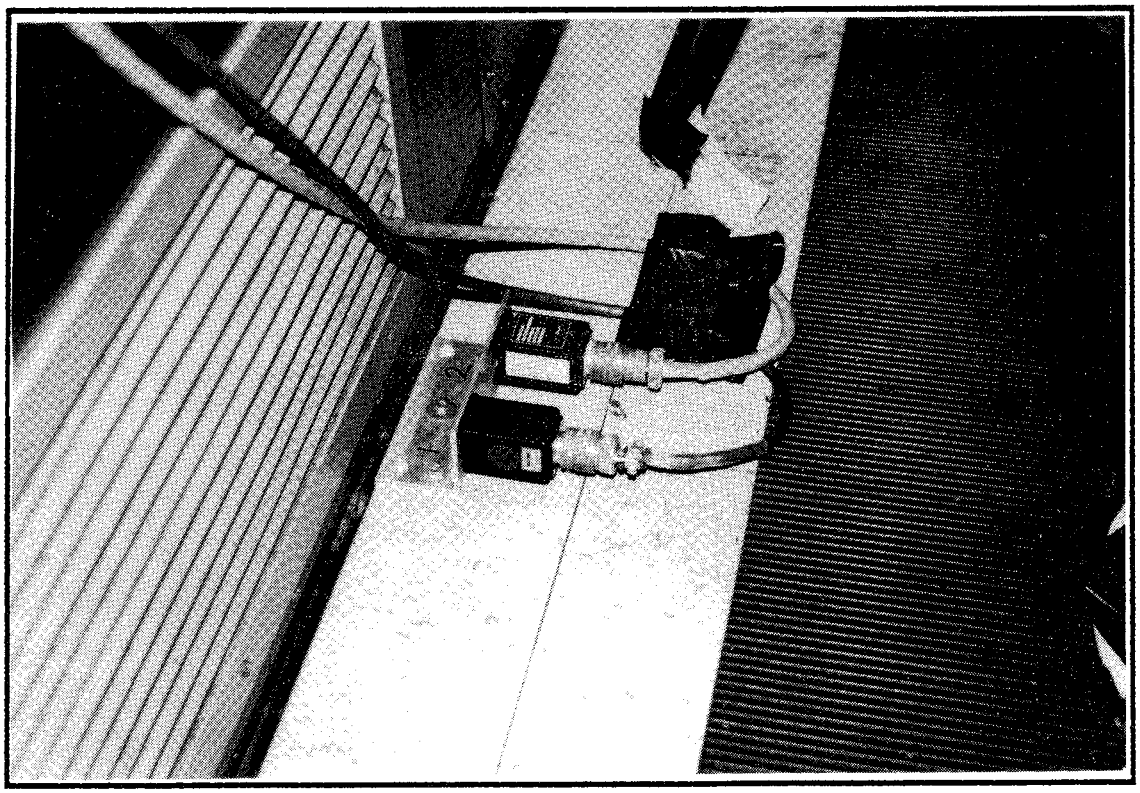


Figure 3. Location of Transducers 1 and 2

Transducer 3 was installed directly above transducers 1 and 2 on the wall near the ceiling as shown in figure 4. This accelerometer was used to measure the car body roll. The accelerometer was also mounted to an aluminum angle bracket. The aluminum was then mounted to the wall with screws flush with the ceiling.

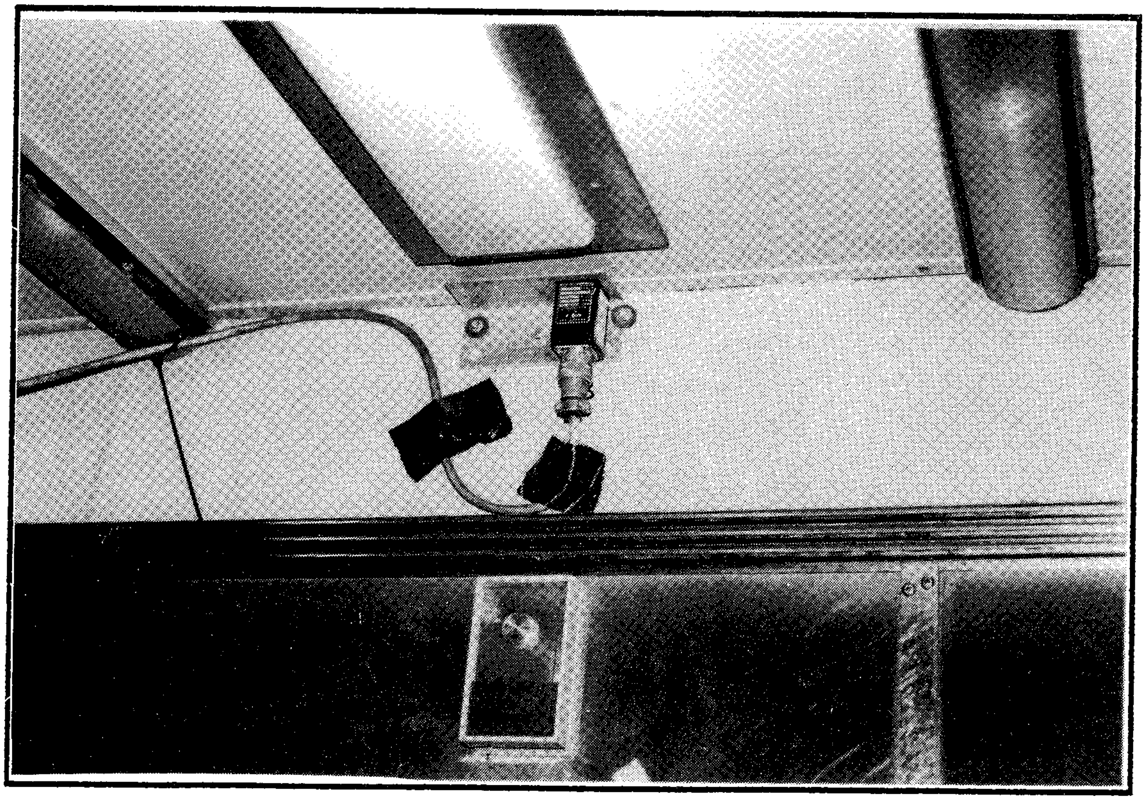


Figure 4. High Lateral Accelerometer on the Passenger Car for Car Body Roll

Transducers 4, 5, and 6 were mounted on the floor at the A-end of the passenger car over the center of the truck (figure 5). The accelerometers were mounted to a section of square aluminum tubing. The section of aluminum was then mounted to the floor of the passenger car at the A-end over the center of the truck.

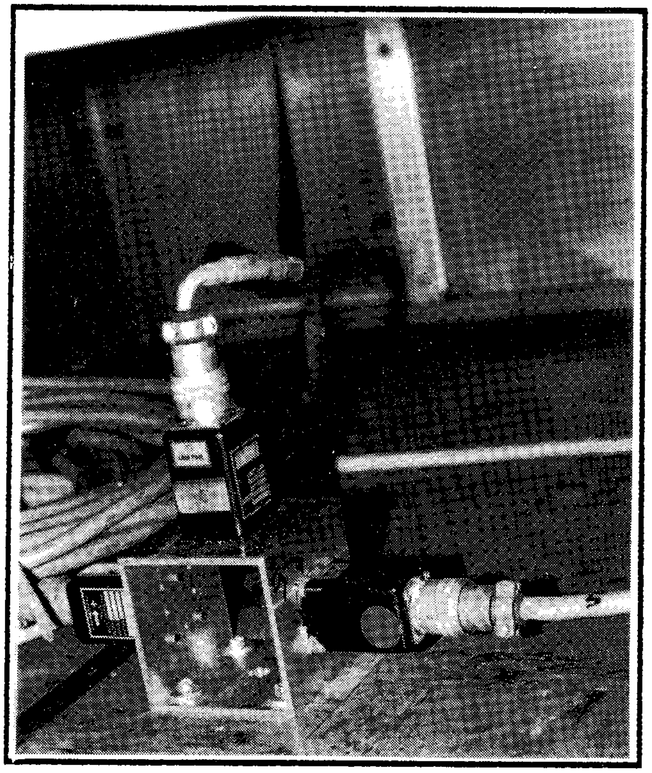


Figure 5. Location of the Accelerometers on A-end of ASF Car Floor

3.3.2 Tank Car Ride Quality Transducers

Transducers 7, 8, and 9 were mounted on the A-end of the tank car over the center of the span bolster (figure 6). The accelerometers were mounted to a section of square aluminum tubing. The section of aluminum was then mounted to the sill of the tank car at the A-end near the center pin.

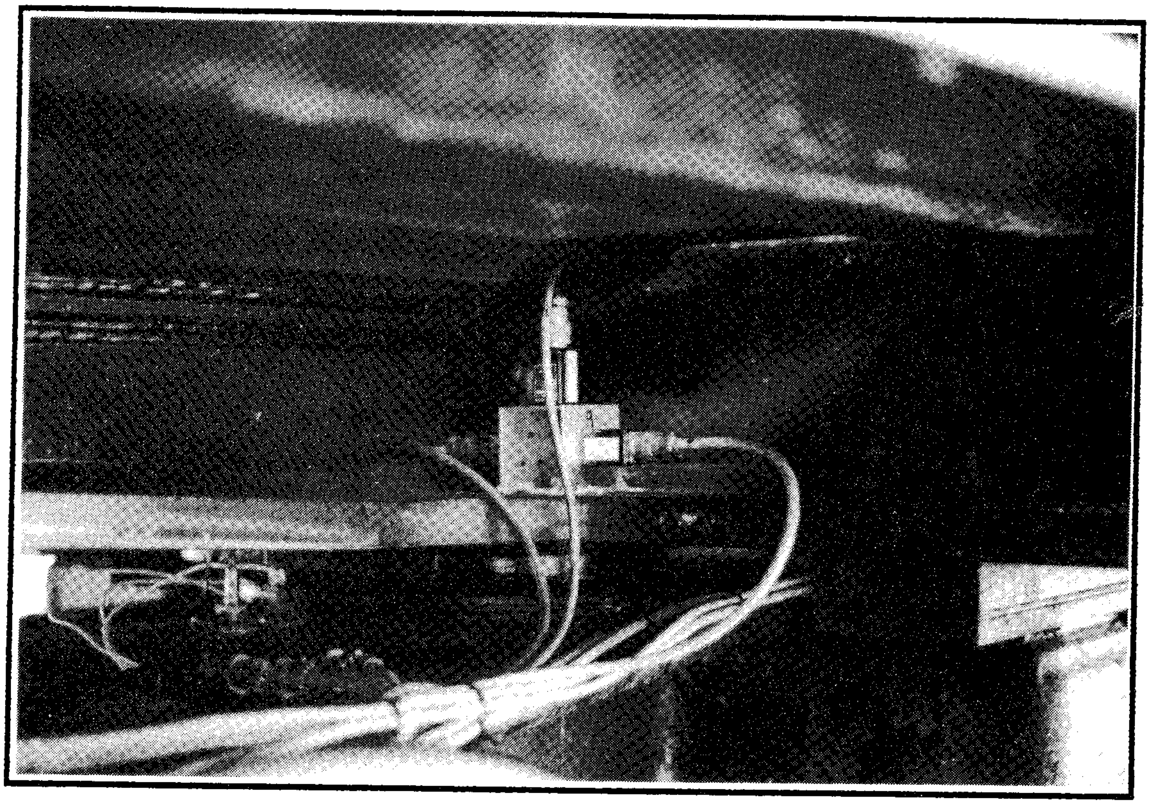


Figure 6. Location of the Accelerometers on the A-end of the Tank Car

Transducers 10 and 11 were mounted on the underside of the tank at mid-car on the center line (figure 7). The accelerometers were mounted to a section of square aluminum tubing. The section of aluminum was then mounted to the underside of the tank.

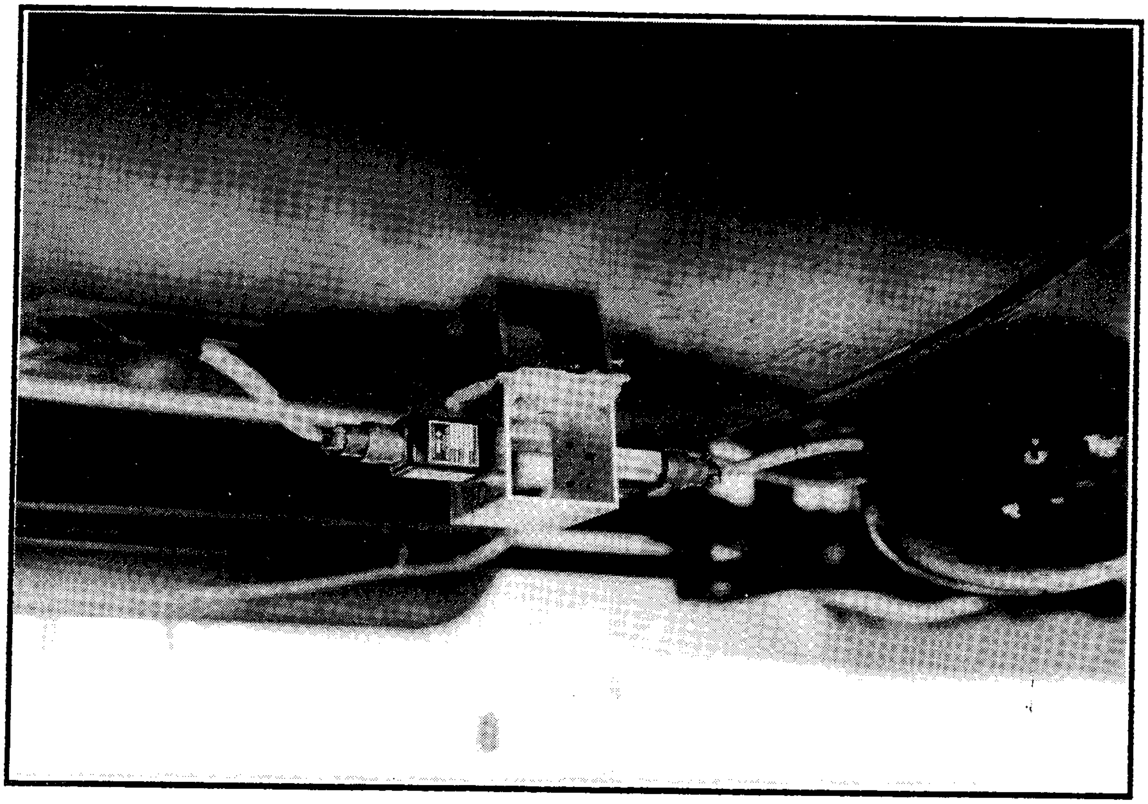


Figure 7. Location of the Accelerometers on the Underside of the Tank Car

Transducer 12 was mounted to a bracket on the top of the tank car. The accelerometer was mounted to an aluminum angle bracket and then held to the tank car bracket with a clamp.

3.3.3 Track Input Transducers

Track input was measured with the LTHD system. The accelerometers, in foam filled boxes, were bolted to the side frame of the leading truck at the location which is usually occupied by the bearing keeper. A vertical and a lateral accelerometer were located on the left side of the truck, and a vertical accelerometer was located on the right side. Figure 8 shows one vertical accelerometer used for the track input as it was connected to the side frame.

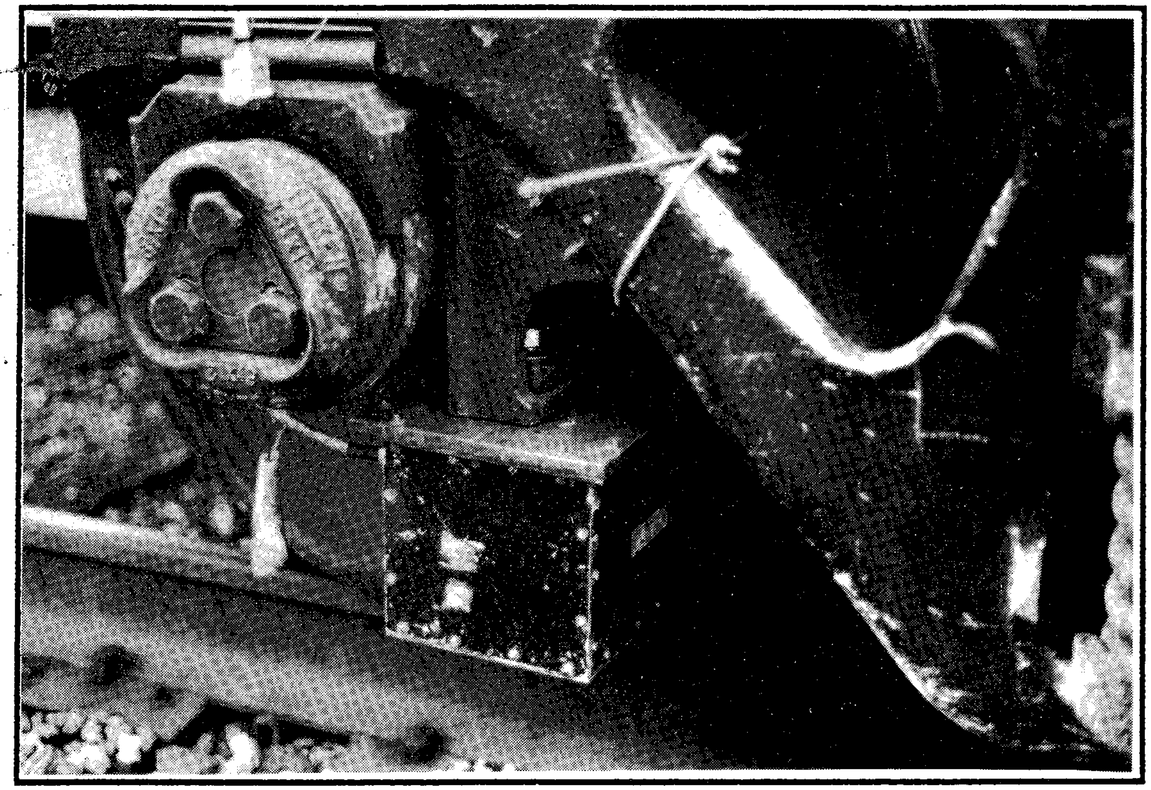


Figure 8. Location of a Track Input Transducer

The roughness of the track was measured with the LTHD accelerometers. The foam was used to dampen the high frequency inputs.

3.3.4 Running Gear Transducers

Transducers 16 and 17 were mounted on the bolster of the leading truck (figure 9) of the tank car and transducers 21 and 22 were mounted on the bolster of the A-end trailing truck of the tank car. The accelerometers were mounted to an aluminum block that was cemented to the bolsters. The surface was ground smooth before the aluminum block was mounted to the bolster.

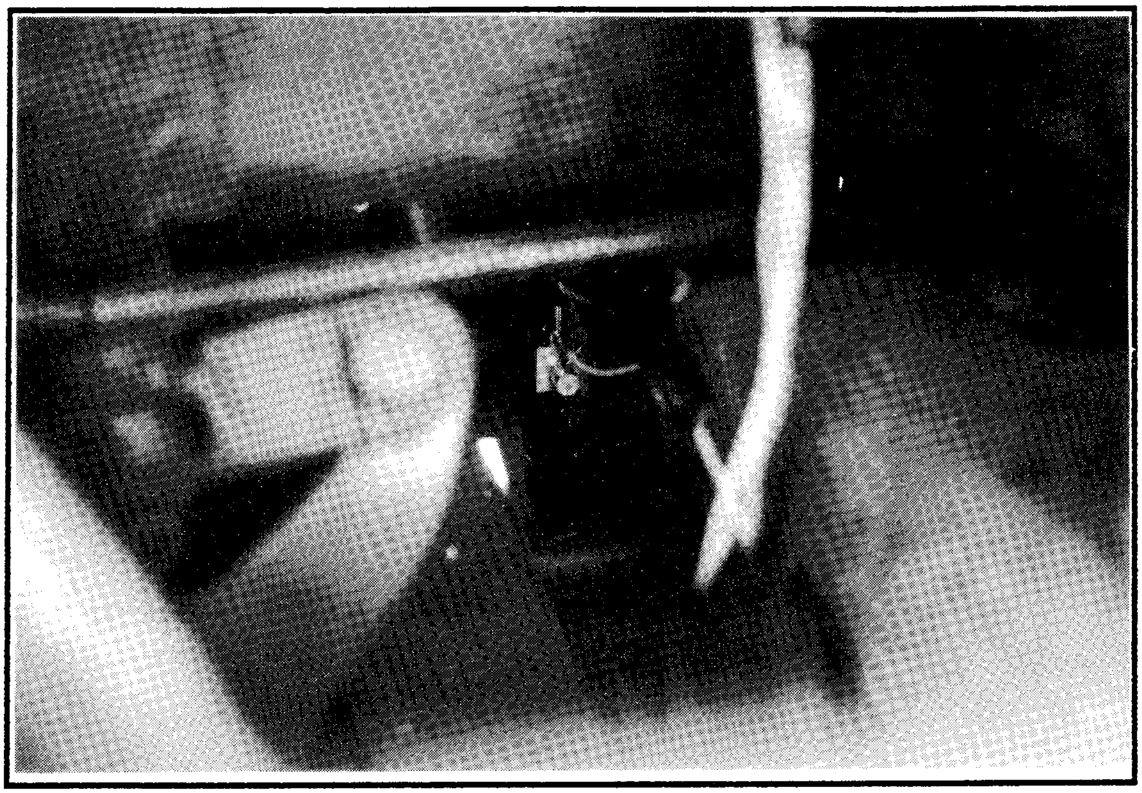


Figure 9. Leading Truck Bolster Accelerometers

Transducers 18, 19, and 20 were mounted on the span bolster near the center pin. The accelerometers were mounted to an aluminum block that was cemented to the bolsters. The surface was ground smooth before the aluminum block was mounted to the bolster.

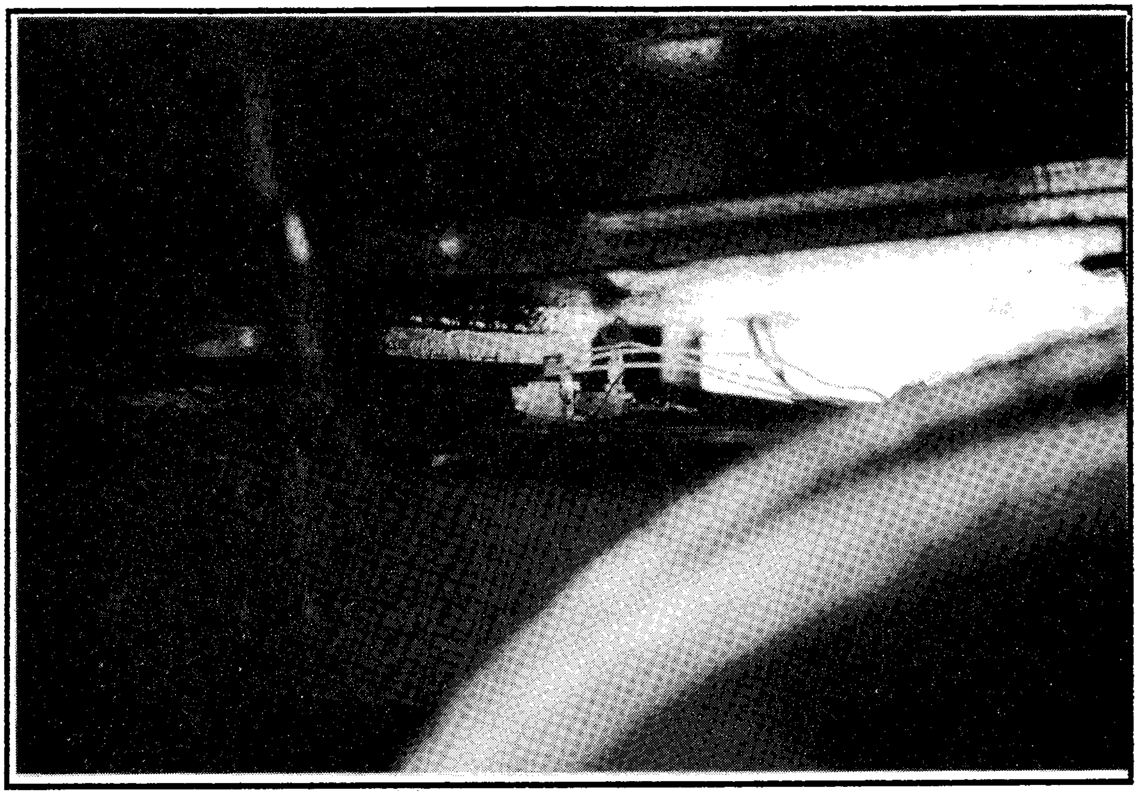


Figure 10. Location of the Span Bolster Accelerometers

3.3.5 High Frequency Transducers

Transducers 24, 25, and 26 were mounted on the span bolster near the center pin. Figure 10 shows the high frequency accelerometers located near the low frequency accelerometers. The accelerometers were mounted to an aluminum block next to the low frequency block.

Transducers 27 and 28 were mounted on the underside of the tank at the middle (figure 11). The accelerometers were mounted to an aluminum block which was cemented to the underside of the tank car near the low frequency accelerometers.

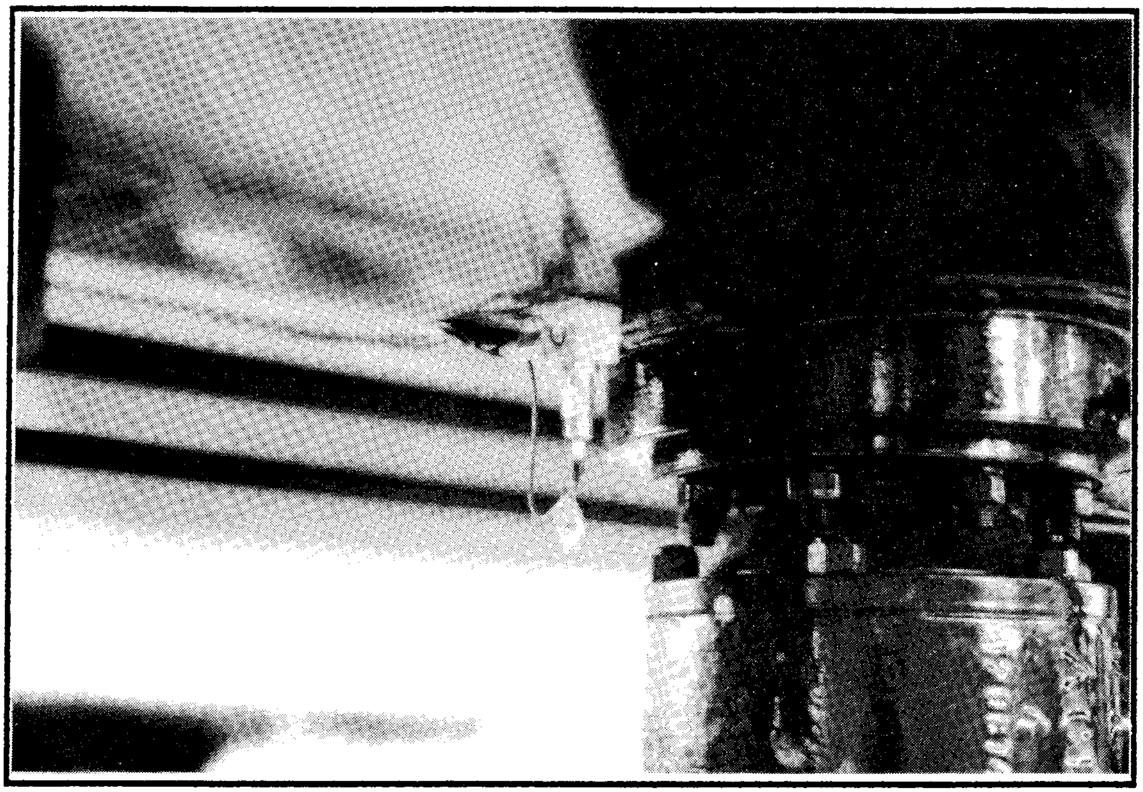


Figure 11. Accelerometers in the Middle of the Tank Car

Transducer 29 was mounted on the bearing adapter of the right side of the leading axle on the tank car. The accelerometer was mounted to an aluminum block that was cemented to the bearing adapter (figure 12).

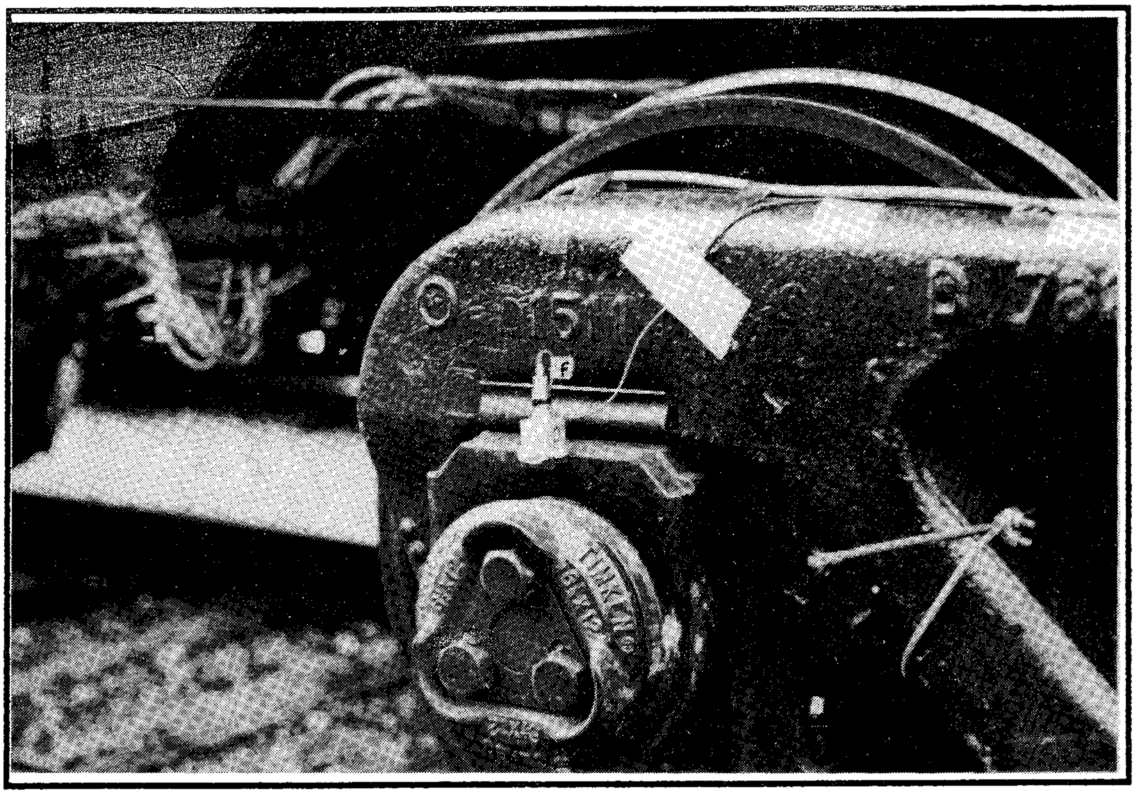


Figure 12. Accelerometer on the Right Axle

Transducers 30 and 31 were mounted on the bearing adapter of the left side of the leading axle on the tank car. The accelerometers were mounted to an aluminum block which was mounted to the left bearing adapter (figure 13).

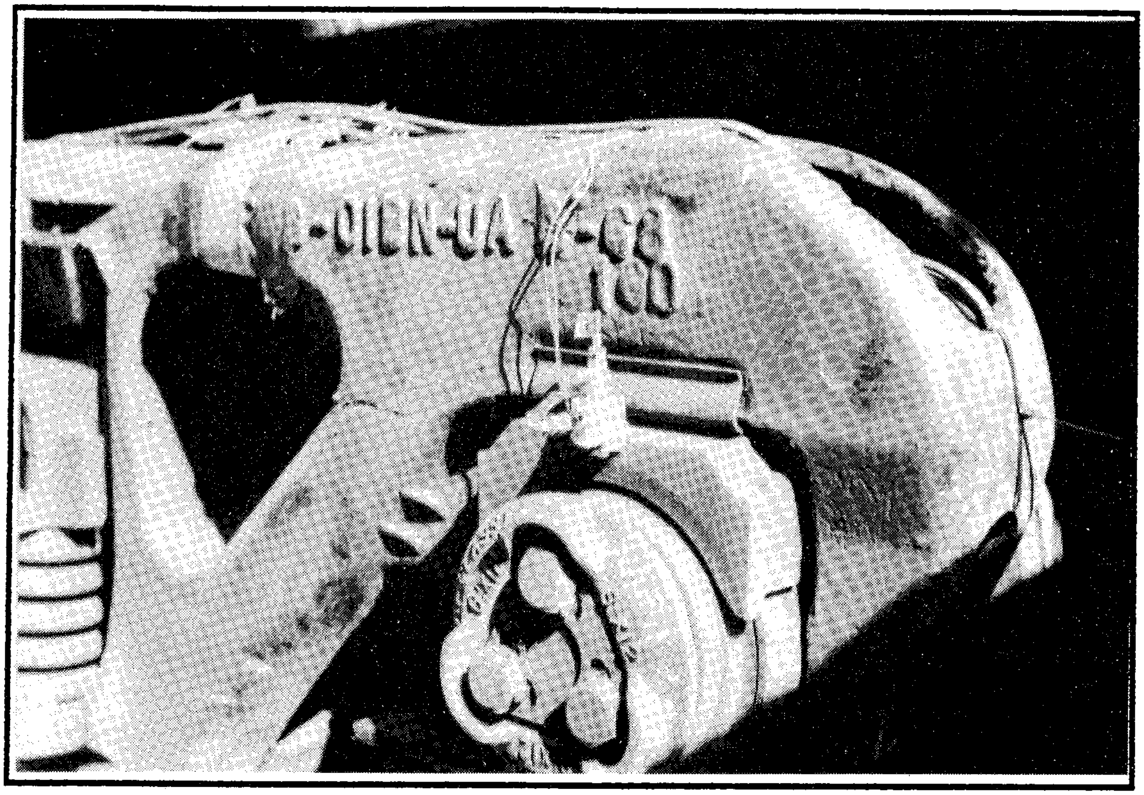


Figure 13. Accelerometers on the Left Axle

4.0 INSTRUMENTATION AND MATERIALS

4.1 TANK CAR DESCRIPTION

Figure 14 shows the DUPX 29769 tank car, which is 92 feet 4 inches long. The loaded weight of the tank car was approximately 526,000 pounds, and the empty weight of the tank car was 133,000 pounds. The stub sill tank car rode on two span bolsters. Each span bolster rode on two standard three-piece freight trucks. Figure 15 shows the configuration of the span bolster and trucks.

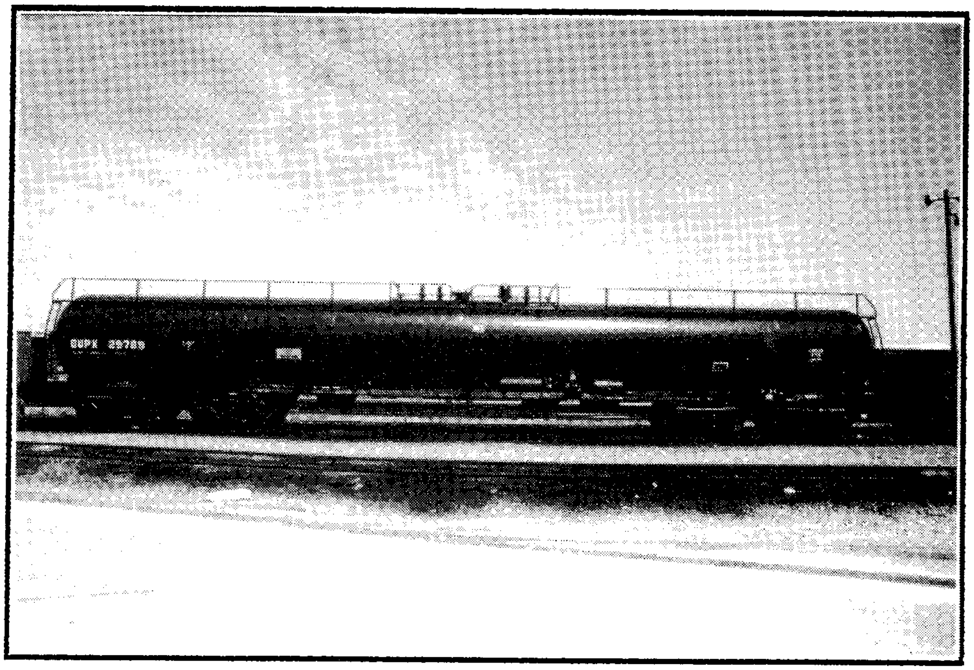


Figure 14. DUPX 29769 Tank Car

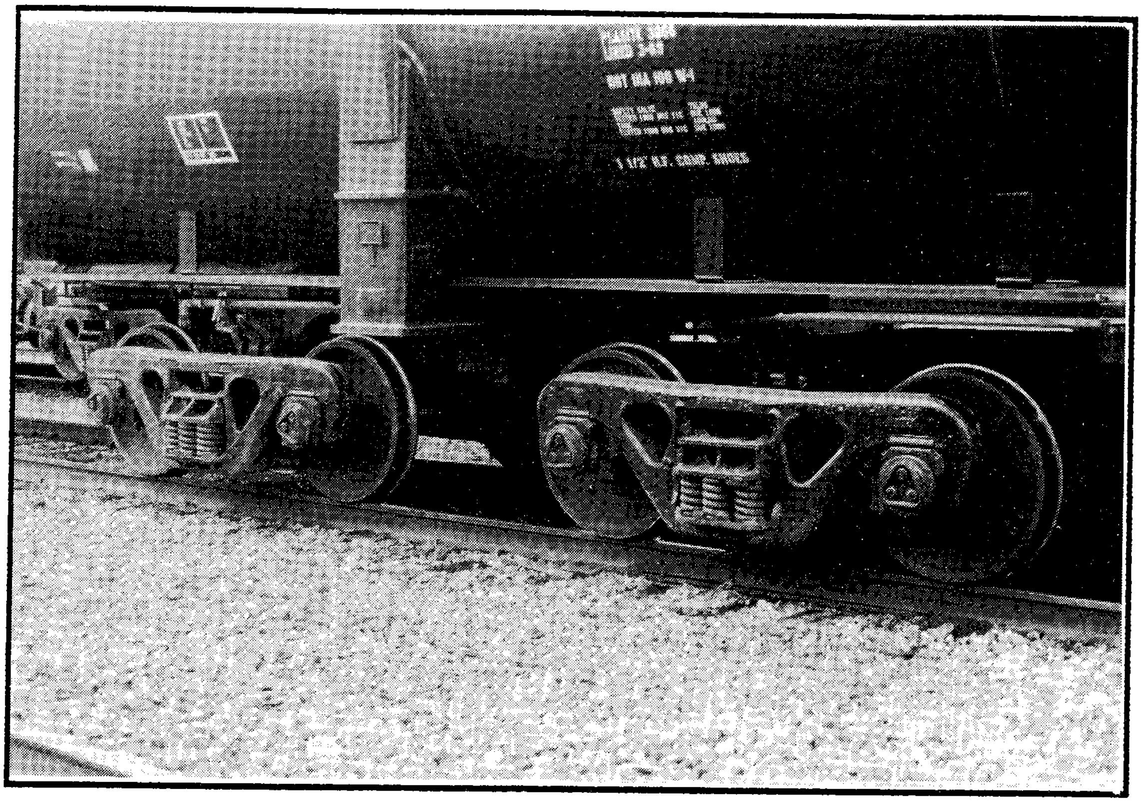


Figure 15. DUPX 29769 Span Bolster and Trucks

4.2 PASSENGER CAR DESCRIPTION

The passenger car used for the ride quality test was the ASFX 1965 Instrumentation Test Car. The car was approximately 78 feet long and weighed 166,000 pounds. This car was used to carry the data acquisition system and test personnel during the ride quality test. Figure 16 shows the ASFX 1965 passenger car. The trucks of the passenger car were different from those of ordinary freight trucks. The ASFX 1965 trucks contained three axles with a leaf spring suspension. Figure 17 shows a truck under the ASFX 1965 passenger car.

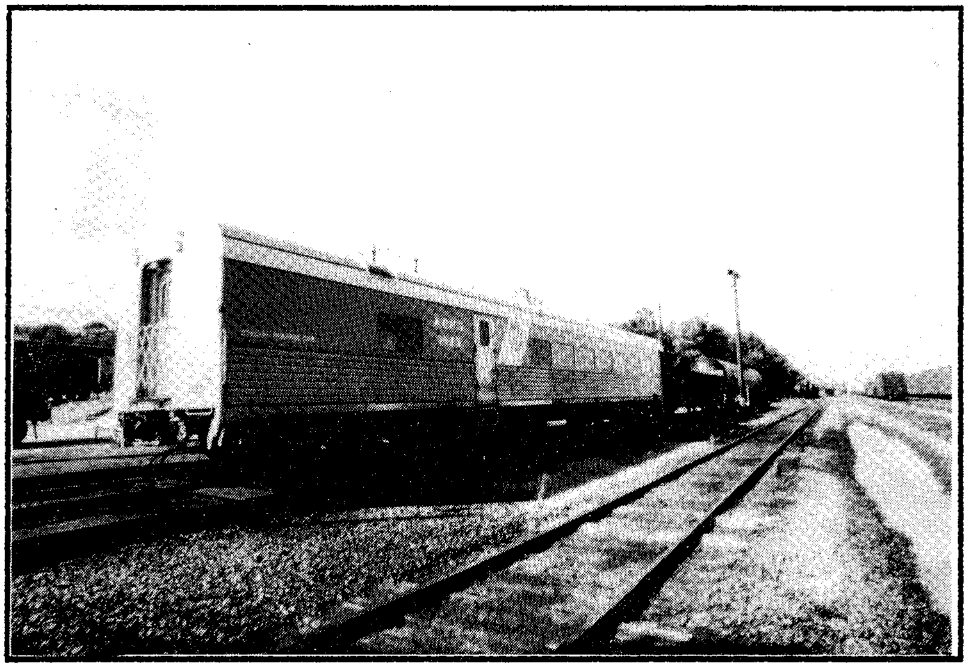


Figure 16. ASFX 1965 Passenger Car

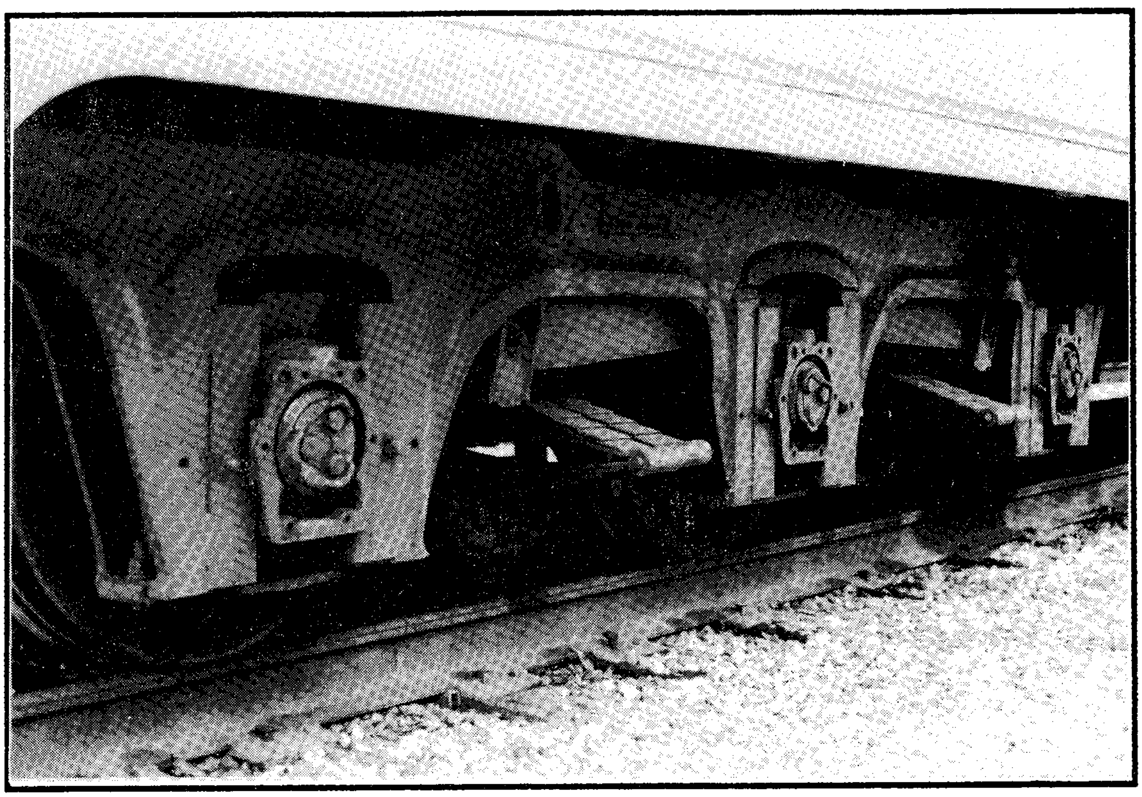


Figure 17. ASFX 1965 Truck

4.3 TEST TRAIN CONFIGURATION

Figure 18 shows the standard test train configuration. The test consist was normally at the head-end of the train with the passenger car leading. Occasionally the test consist was in the middle or at the end of the train due to restrictions by the "B" Railroad. At one time the test train consist was at the head of the train with the tank car leading.

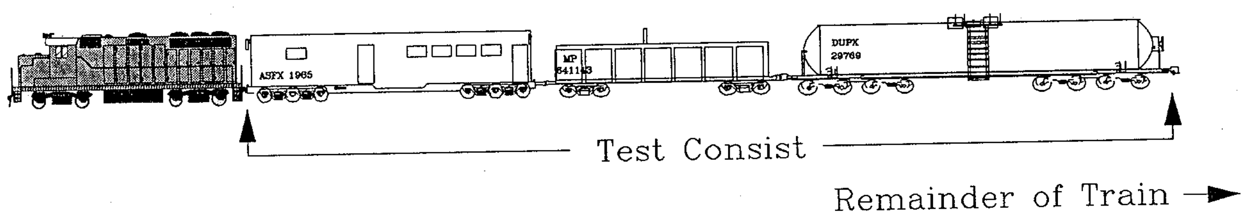


Figure 18. Standard Test Setup

4.4 DATA ACQUISITION

Two separate systems were used to collect 32 channels of data, one for low frequency and one for high frequency. Table 2 lists the names of all the channels that were recorded and their location in an XYZ coordinate system. The origin of the coordinate system is at the top of the rail head at the leading axle of each car (B-end) in the center of the track. So there is a separate origin for the tank car and the passenger car. Positive longitudinal acceleration is in the direction of travel and is denoted by **X** (towards the B-end in this case), positive lateral acceleration is to the right as you are looking at the B-end of the car and is denoted by **Y**, and positive vertical acceleration is up from the ground and is denoted by **Z**. Figure 19 is a pictorial of the XYZ coordinate system.

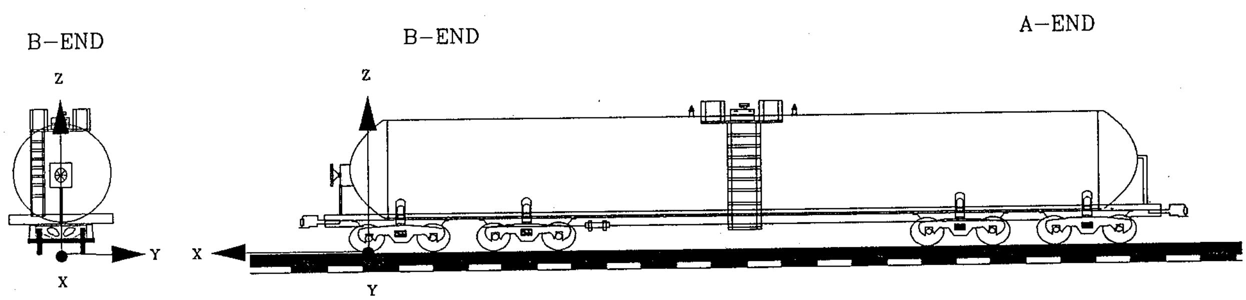


Figure 19. XYZ Coordinate System

Table 2. Channel Names and Locations

Channel Name	Channel Description	X (in.)	Y (in.)	Z (in.)
AMCV	Passenger car, middle of car body, vertical	-355.5	0.0	50.8
AMCL	Passenger car, middle of car body, lateral	-355.5	0.0	50.8
AMCH	Passenger car, middle of car body, high lateral	-354.0	0.0	140.8
AACV	Passenger car, A-end car body, vertical	-49.5	0.0	50.8
AACL	Passenger car, A-end car body, lateral	-46.5	0.0	50.8
AACN	Passenger car, A-end car body, longitudinal	-48.0	0.0	52.8
DACV	Tank car, A-end car body, vertical	-96.0	12.5	43.5
DACL	Tank car, A-end car body, lateral	-96.0	14.0	45.0
DACN	Tank car, A-end car body, longitudinal	-96.0	15.5	43.5
DMCV	Tank car, middle of car body, vertical	-406.0	0.0	47.5
DMCL	Tank car, middle of car body, lateral	-409.0	0.0	47.5
DMCH	Tank car, middle of car body, high lateral	-411.5	0.0	
LTLV	Tank car, LTHD axle 1 left, vertical	-7.0	-38.0	9.0
LTRV	Tank car, LTHD axle 1 right, vertical	-7.0	-38.5	9.0
LTRL	Tank car, LTHD axle 1 right, lateral	-7.0	-36.0	9.0
DLTV	Tank car, leading truck bolster, vertical	-27.0	0.0	19.0
DLTL	Tank car, leading truck bolster, lateral	-27.0	0.5	18.0
DSBV	Tank car, span bolster, vertical	-92.0	0.0	45.0
DSBL	Tank car, span bolster, lateral	-92.0	0.0	44.5
DSBN	Tank car, span bolster, longitudinal	-91.5	0.0	44.5
DTTV	Tank car, trailing truck bolster, vertical	-171.5	0.0	18.5
DTTL	Tank car, trailing truck bolster, lateral	-171.5	0.5	18.0
TSPD	Train speed	-	-	-
ALD	Manual location device	-	-	-
HF1	High frequency, tank car, span bolster, vertical	-90.5	0.0	45.0
HF2	High frequency, tank car, span bolster, lateral	-91.0	0.0	44.5
HF3	High frequency, tank car, span bolster, longitudinal	-91.0	0.0	44.5
HF4	High frequency, tank car, mid. car body, vertical	-462.5	0.0	48.0
HF5	High frequency, tank car, middle of car body, lateral	-462.5	0.5	48.5
HF6	High frequency, tank car, axle 1 left, vertical	0.0	44.5	25.5
HF7	High frequency, tank car, axle 1 right, vertical	0.0	-44.5	25.5
HF8	High frequency, tank car, axle 1 right, lateral	0.0	-45.0	25.0

4.4.1 Low Frequency

Low frequency data was routed through Pacific signal conditioning and filtered at 30 Hz. The data was then collected on an HP 330 computer via an HP 6944A multiprogrammer. The data was collected at a rate of 300 samples per second. The eight channels that were noted in Table 1 were also recorded on a Western Graftec strip chart. The speed channel was collected at 300 samples per second but was not filtered. The LTHD channels were collected at 300 samples per second and filtered at 1 Hz to provide an accurate geometry of the track.

4.4.2 High Frequency

High frequency data was routed through a PCB pre-amplifier and then to the Pacific signal conditioning where the signal was filtered at 2000 Hz. As with the low frequency data, the signal was then collected on an HP 330 computer via an HP 6944A multiprogrammer. The data was collected at a sample rate of approximately 9200 samples per second. The sample rate was limited by the throughput of the computer and the multiprogrammer and was set as fast as possible.

4.5 INSTRUMENTATION

Several devices and components were used to acquire each channel of data and are described in detail in this section. Table 1 lists the type of device that was used.

4.5.1 Accelerometers

Five different types of accelerometers were used. Table 3 lists these accelerometers and the location where each was used.

Table 3. Types of Accelerometers

Channel Name	Type	Serial Number	Sensitivity
AMCV	Systron Donner	00932	5.018 V/G
AMCL	Systron Donner	00922	5.012 V/G
AMCH	Systron Donner	00934	5.000 V/G
AACV	Systron Donner	00924	5.047 V/G
AACL	Systron Donner	00921	5.003 V/G
AACN	Systron Donner	00935	4.991 V/G
DACV	Systron Donner	03057	4.990 V/G
DACL	Systron Donner	00929	4.957 V/G
DACN	Systron Donner	00931	4.990 V/G
DMCV	Systron Donner	00928	5.004 V/G
DMCL	Systron Donner	00927	4.990 V/G
DMCH	Systron Donner	19753	2.341 V/G
LTLV	Schaevitz	22570	0.98680 V/G
LTRV	Schaevitz	21706	0.99380 V/G
LTRL	Schaevitz	21712	0.99480 V/G
DSBV	Setra	14032	0.03427 V/G
DSBL	Setra	14038	0.02713 V/G
DSBN	Setra	14027	0.03430 V/G
DLTV	Endevco	BK92	0.01118 V/G
DLTL	Endevco	BP19	0.01164 V/G
DTTV	Endevco	BL03	0.01109 V/G
DTTL	Endevco	BM52	0.01013 V/G
HF1	PCB Piezoelectric	D4612F	0.00988 V/G
HF2	PCB Piezoelectric	D4544F	0.01000 V/G
HF3	PCB Piezoelectric	D4582F	0.00984 V/G
HF4	PCB Piezoelectric	D4595F	0.01001 V/G
HF5	PCB Piezoelectric	D4620F	0.00997 V/G
HF6	PCB Piezoelectric	D4589F	0.01009 V/G
HF7	PCB Piezoelectric	D4615F	0.00986 V/G
HF8	PCB Piezoelectric	D4584F	0.01003 V/G

4.6 INSTRUMENTATION CALIBRATION

After all of the transducers were in place, the entire system was calibrated. Table 4 lists the system engineering units per volt and the system volts per engineering units for all 32 channels.

Table 4. System Calibration

Channel Number	Channel Name	System Engineering Unit's / Volt	System Volts / Engineering Units's
1	AMCV	0.1993 G/V	5.0180 V/G
2	AMCL	0.1995 G/V	5.0120 V/G
3	AMCH	0.2000 G/V	5.0000 V/G
4	AACV	0.1981 G/V	5.0470 V/G
5	AACL	0.1999 G/V	5.0030 V/G
6	AACN	0.2004 G/V	4.9910 V/G
7	DACV	0.2004 G/V	4.9900 V/G
8	DACL	0.2017 G/V	4.9570 V/G
9	DACN	0.2004 G/V	4.9900 V/G
10	DMCV	0.1998 G/V	5.0040 V/G
11	DMCL	0.2004 G/V	4.9900 V/G
12	DMCH	0.4272 G/V	2.3410 V/G
13	LTLV	0.0507 G/V	19.7360 V/G
14	LTRV	0.0503 G/V	19.8760 V/G
15	LTRL	0.0503 G/V	19.8960 V/G
16	DLTV	0.8945 G/V	1.1180 V/G
17	DLTL	0.8591 G/V	1.1640 V/G
18	DSBV	0.5836 G/V	1.7135 V/G
19	DSBL	0.7372 G/V	1.3565 V/G
20	DSBN	0.5831 G/V	1.7150 V/G
21	DTTV	0.9017 G/V	1.1090 V/G
22	DTTL	0.9872 G/V	1.0130 V/G
23	TSPD	20.0000 MPH/V	0.0500 V/MPH
24	ALD	0.3333 EVE/V	3.0003 V/EVE
25	HF1	101.2146 G/V	0.0099 V/G
26	HF2	10.0000 G/V	0.1000 V/G
27	HF3	10.1626 G/V	0.0984 V/G
28	HF4	99.9001 G/V	0.0100 V/G
29	HF5	10.0301 G/V	0.0997 V/G
30	HF6	99.1080 G/V	0.0101 V/G
31	HF7	101.4199 G/V	0.0099 V/G
32	HF8	9.9701 G/V	0.1003 V/G

5.0 RESULTS

More than five gigabytes of data were collected during this test. Data was collected continuously while the test consist was in motion. The data was analyzed in two sections, the loaded tank car and the empty tank car. The data was also split into four speed categories. The categories were 15 - 24 mph, 25 - 39 mph, 40 - 49 mph, and 50+ mph. These were sufficient to categorize the car vibrations.

5.1 LOW FREQUENCY DATA

The first process on the low frequency data was to calculate and plot power spectral densities (PSD) for the loaded tank car and the empty tank car at the four speed categories. PSD's were calculated for blocks of data where the speed was somewhat constant; therefore, not **ALL** of the data was covered due to speed variations. Appendix A contains the PSD's for all of the low frequency data during the portion of the trip when the tank car was loaded. Appendix B contains all of the low frequency PSD's for the empty tank car portion. These PSD plots also contain a root mean square (RMS) value that gives the overall acceleration level in g's of that channel. The second procedure for the low frequency data was to filter the six channels that were used for ride quality at each speed category. These channels were filtered with a standard ISO filter for ride quality (figure 20).

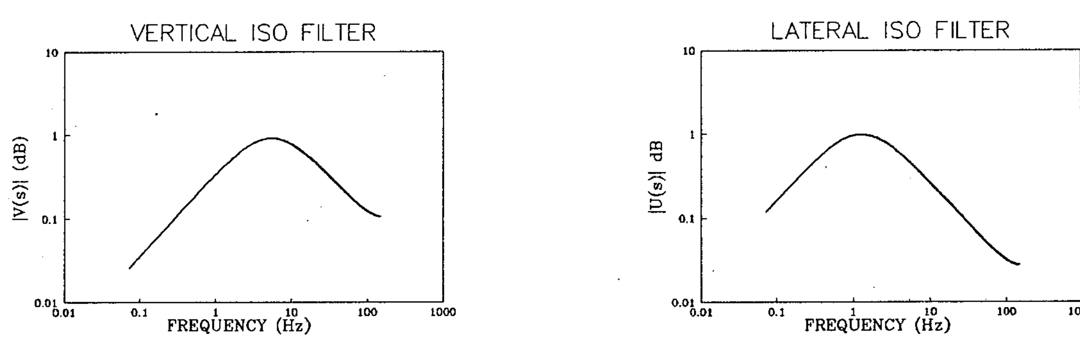


Figure 20. ISO Ride Quality Filters

The filters are described by the equations in Table 5 below.

Table 5. ISO Ride Quality Filters

Vertical Filter	Lateral and Longitudinal Filters
$\frac{V_1(s)}{V_0(s)} = \frac{3.25}{1+\sqrt{2}\cdot\left(\frac{s}{\omega_0}\right)+\frac{s^2}{\omega_0^2}}$ $\frac{V_2(s)}{V_0(s)} = \frac{1.4}{\left(1+\frac{s}{\omega_2}\right)}\cdot\frac{\left(0.1+\frac{s}{\omega_1}\right)}{\left(1+\frac{s}{\omega_1}\right)}$	$\frac{U_1(s)}{U_0(s)} = \frac{1+\sqrt{2}\cdot\left(\frac{s}{\omega_3}\right)}{1+\sqrt{2}\cdot\left(\frac{s}{\omega_3}\right)+\left(\frac{s^2}{\omega_3^2}\right)}$ $\frac{U_2(s)}{U_0(s)} = \frac{1}{1+\frac{s}{\omega_3}}$

where

$\omega_0 = (2\pi)(0.3)$

$\omega_1 = (2\pi)(4)$

$\omega_2 = (2\pi)(8)$

$\omega_3 = (2\pi)(2)$

$s = j\omega$

and

$V_{total} = V_1 + V_2$

$U_{total} = 0.5\,(U_1 + U_2)$

After the ride quality channels were filtered, statistics were run to find an average and maximum RMS value for each speed category. These values were averaged and then placed on graphs with the ISO fatigue and decreased proficiency limits. The loaded and empty configurations were treated separately. Each speed category and vibration direction was used. Appendix C contains the 24 graphs that describe the individual directions of vibration for both the loaded and empty tank car portions of the test. It can be seen that the vibration level increases with higher speeds, and it can also be seen that the 8-hour fatigue and decreased proficiency limit is reached quite easily most of the time on the tank car. The passenger car had a better ride at slower speeds, but it also reached the 8-hour fatigue and decreased proficiency limit at speeds greater than 50 mph.

To convert all of the vibration directions into one overall vibration level, equation (1) must be used. [1] This equation converts the vertical, lateral, and longitudinal vibrations into one overall vibration level. This overall vibration level is then plotted on the ISO fatigue and decreased proficiency limits scale for vertical vibration. Each direction is as follows:

a_x = longitudinal,

a_y = lateral,

a_z = vertical.

$$a_w = \sqrt{(1.4 \cdot a_x)^2 + (1.4 \cdot a_y)^2 + (a_z)^2} \qquad (1)$$

1 Air Standardization Coordinating Committee, Advisory Publication, "Vibration Exposure Limits," Assc. Adv. Pub. 61/17A, 18 August 1982.

Figure 21 shows the overall vibration on the fatigue and decreased proficiency limits at 15 - 24 mph for the loaded tank car. This chart shows that the middle of the tank car had an average vibration level that would be considered a 3-hour limit. Both the middle and A-end of the tank car were above the 8-hour limit, while the passenger car vibration level was worse at the A-end and only in the 16-hour limit in the middle of the car. In the range of 15 - 24 mph, the middle of the tank car had a rougher ride than the passenger car.

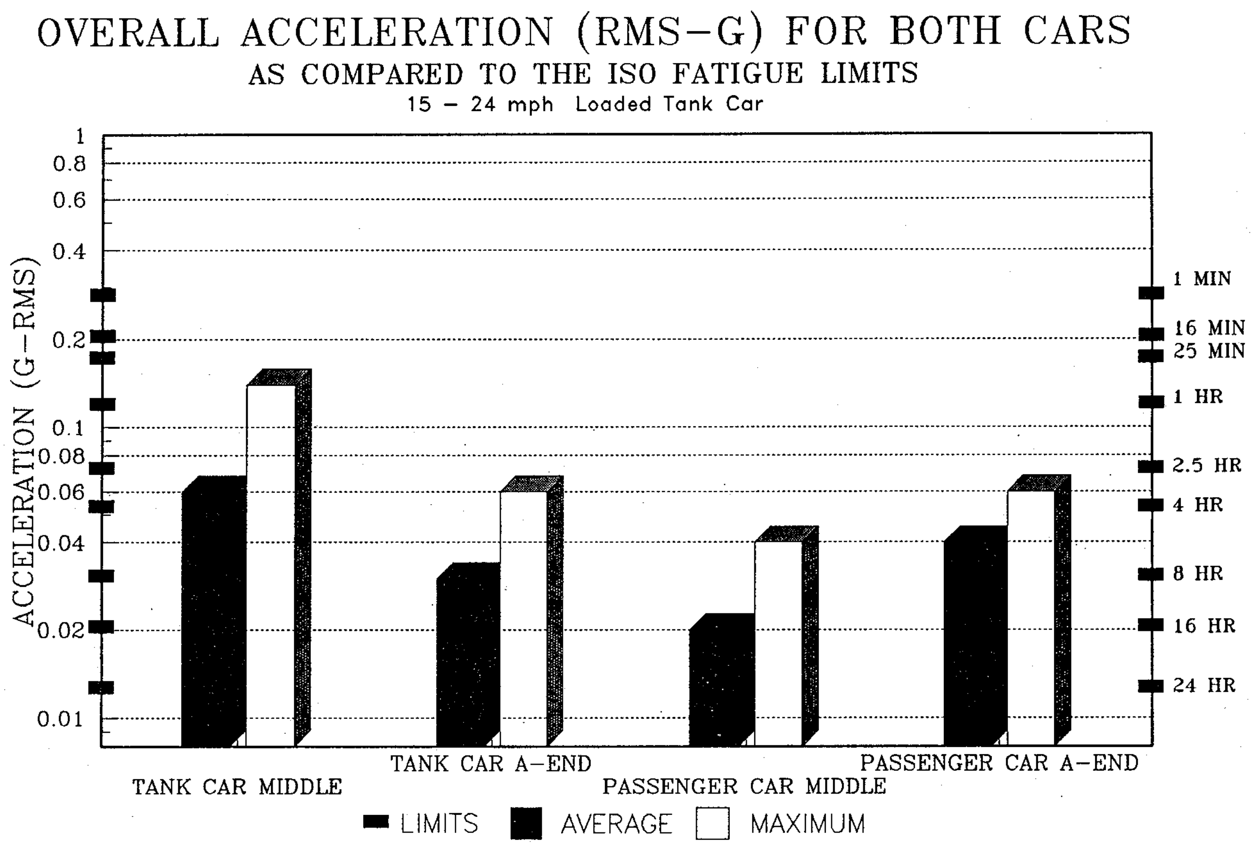


Figure 21. Loaded Tank Car 15 - 24 mph Vibration Levels

Figure 22 shows the overall vibration level at 25 - 39 mph for the loaded tank car. These vibration levels are also compared against the fatigue and decreased proficiency limits. The tank car had the same level of vibration as the passenger car at the A-end, which was in the 8-hour limit. The middle of the tank car had a vibration level that would be in the 2-hour limit, while the middle of the passenger car was still in the 16-hour range. Again the tank car had a higher vibration level than the passenger car.

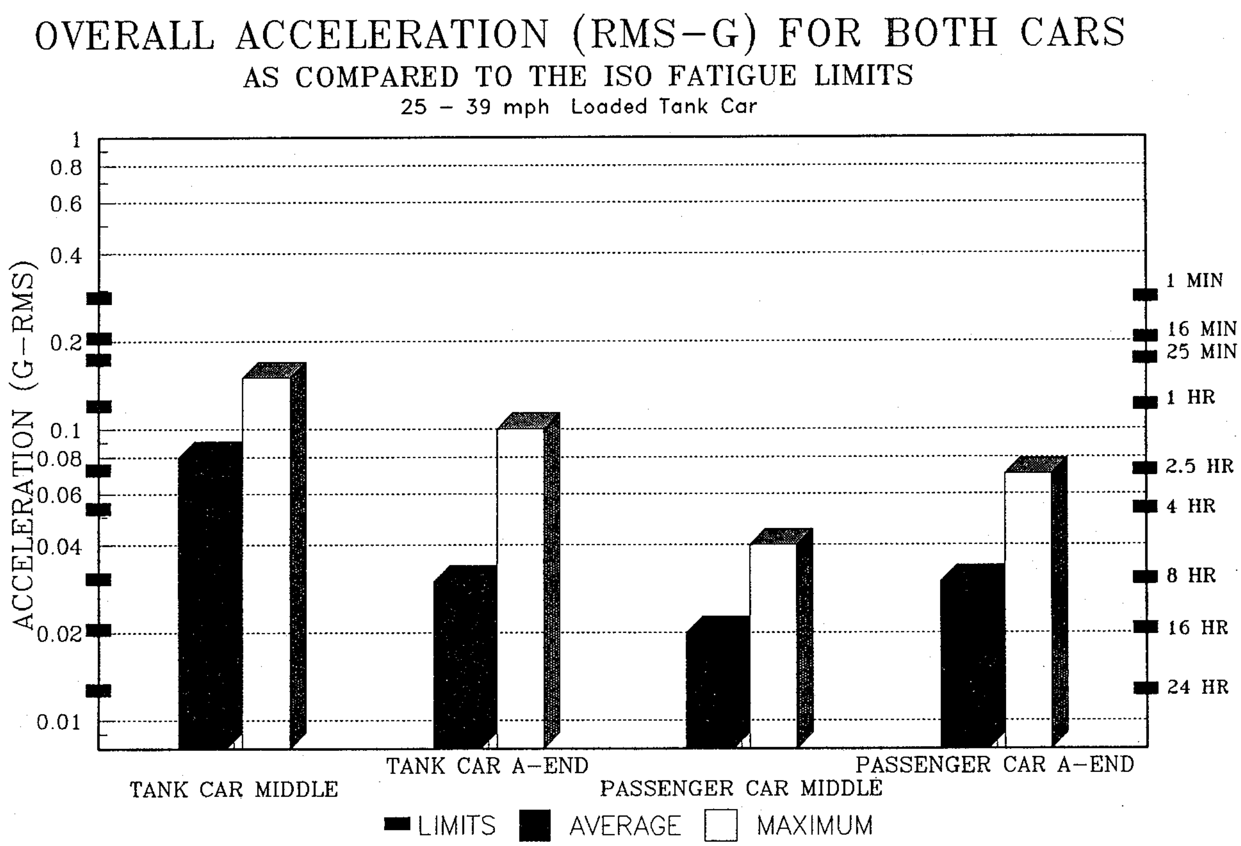


Figure 22. Loaded Tank Car 25 - 39 mph Vibration Levels

Figure 23 charts the vibration level of the loaded tank car versus the passenger car in a speed range of 40 - 49 mph. Here it can be seen that the passenger car is beginning to receive higher vibrations. The middle of the passenger car is now at the 8-hour limit, along with the A-end of the car. The tank car is also encountering higher vibration levels in this speed range. The middle of the tank car is in the 1.5 hour range and the A-end of the tank car is at the 5-hour limit. This shows that the passenger car is riding rougher, but the tank car vibration level is also increasing.

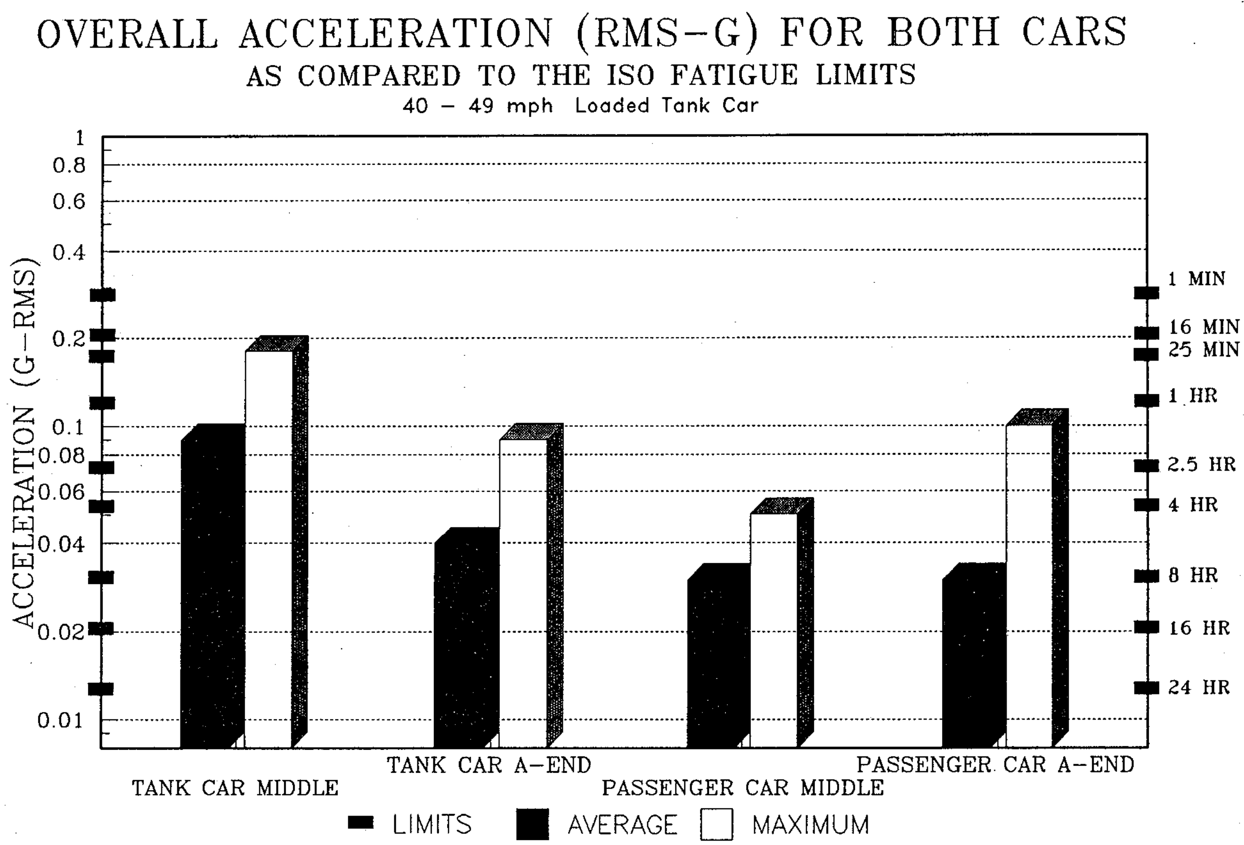


Figure 23. Loaded Tank Car 40 - 49 mph Vibration Levels

Finally, figure 24 shows the loaded tank car in the 50+ mph range. Here the passenger car and tank car vibration levels increased slightly. The A-end of the passenger car increased to the 4.5 hour limit and the middle of the tank car increased to the 1.25 hour limit. This shows that the loaded tank car vibration levels increased as the speed increased; this decreased the exposure time for a passenger. The passenger car also saw a rougher ride as the speed increased, but the exposure limit was never less than 4.5 hours.

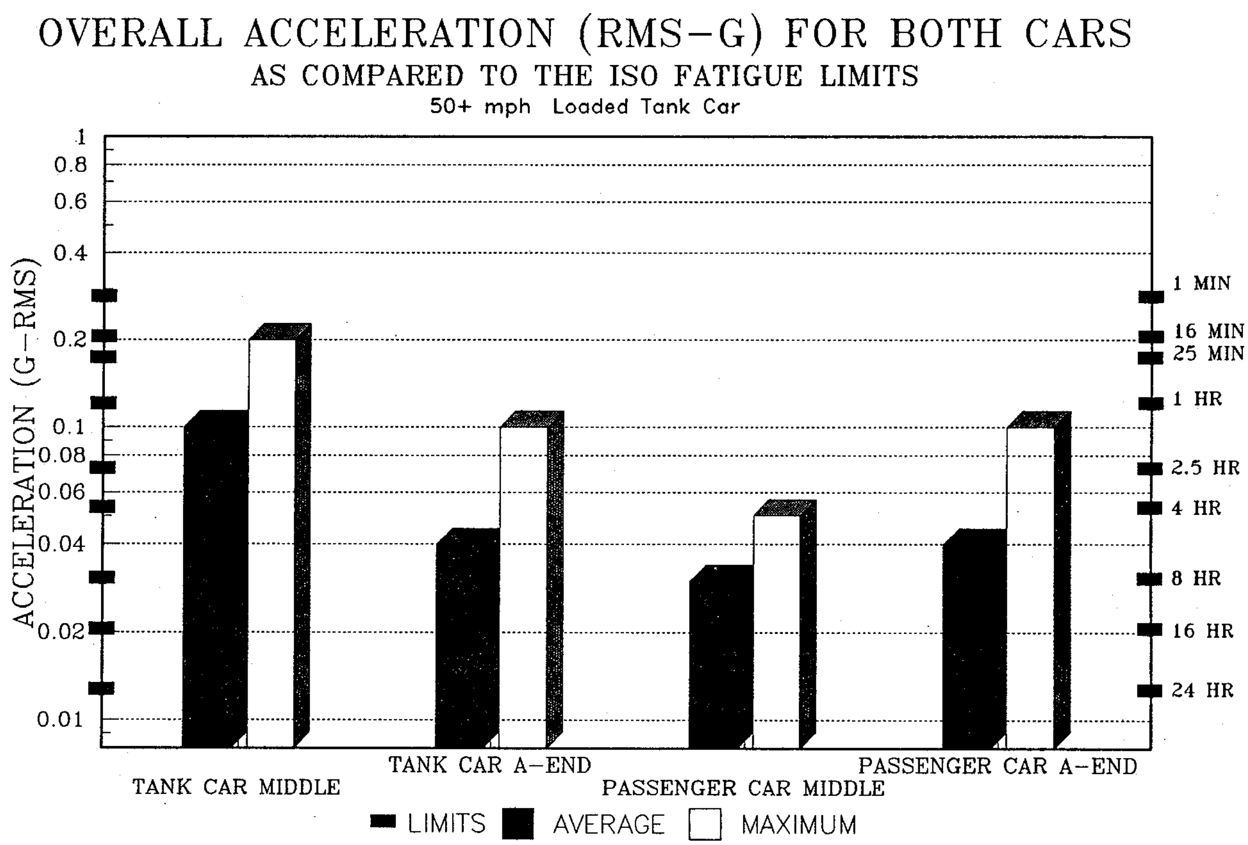


Figure 24. Loaded Tank Car 50+ mph Vibration Levels

Two things about the tank car ride were very clear. First, the vibration level increased with speed and second, the middle of the tank car had higher vibration levels than the A-end of the car. The high vibration levels can be attributed to rigid and flexible body modes as well as track input.

Figure 25 is a PSD of the vertical accelerometer in the middle of the tank car. There are three large peaks and one smaller peak in the 0-12 Hz range. These frequencies are important as the ISO weighting filter is essentially a 4-8 Hz band pass filter. The small spike at approximately 4 Hz seems to be a combination of pitch and bounce. These rigid body modes are usually closely coupled. The spike at 6 Hz is difficult to explain. It is so low on the A-end of the car that it is not visible on the linear scale PSD shown in figure 26. The middle of the car was in phase with the A-end at 6 Hz. This would not lend itself to a vertical bending motion; it seems to be a flexible mode but may couple with the span bolsters and trucks in some way. A more detailed analysis (finite element) or more testing (modal analysis) would be necessary to explain the 6 Hz phenomenon. The spike at 9 Hz is related to input from the wheels directly. Nine Hz is the frequency at which a 36-inch wheel rotates when traveling at approximately 58 mph. This may be likened to "road noise" in an automobile. The 9 Hz road noise at the middle of the tank car is slightly less than twice that at the A-end. This is due to the sum of the inputs at both the A and B ends of the car. The car body does slightly damp the 9 Hz.

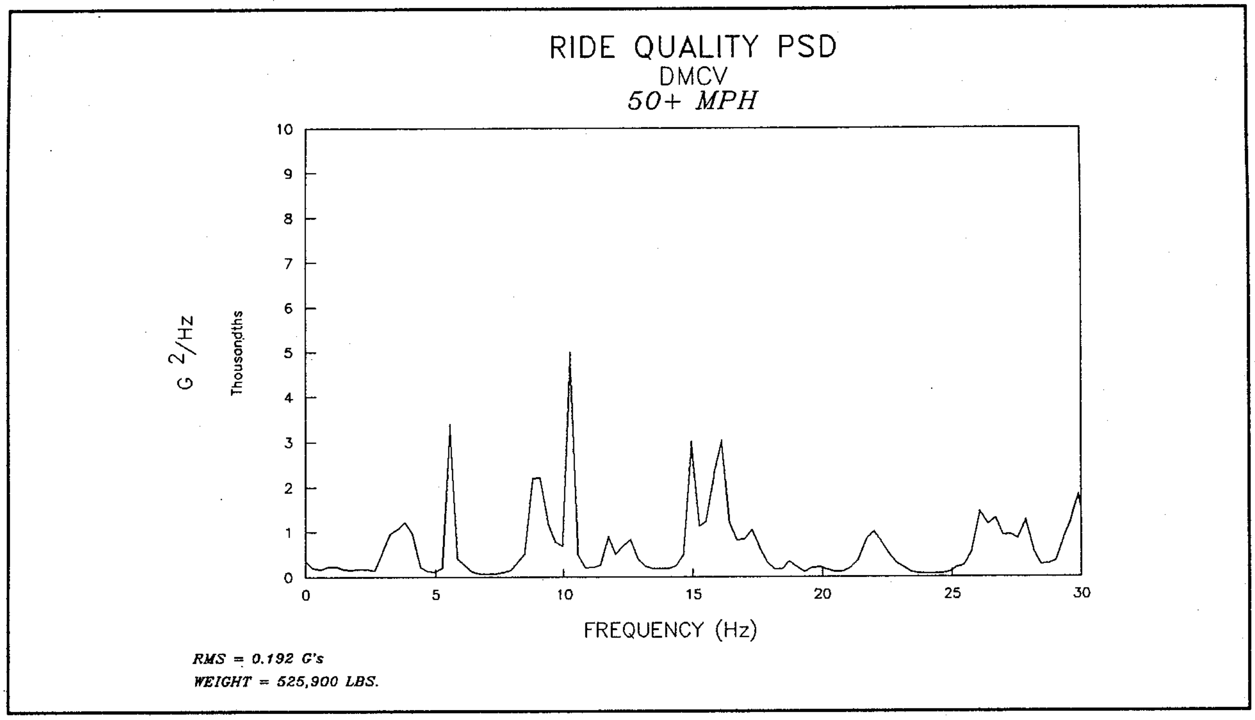


Figure 25. Tank Car Mid-car Vertical Accelerometer PSD.

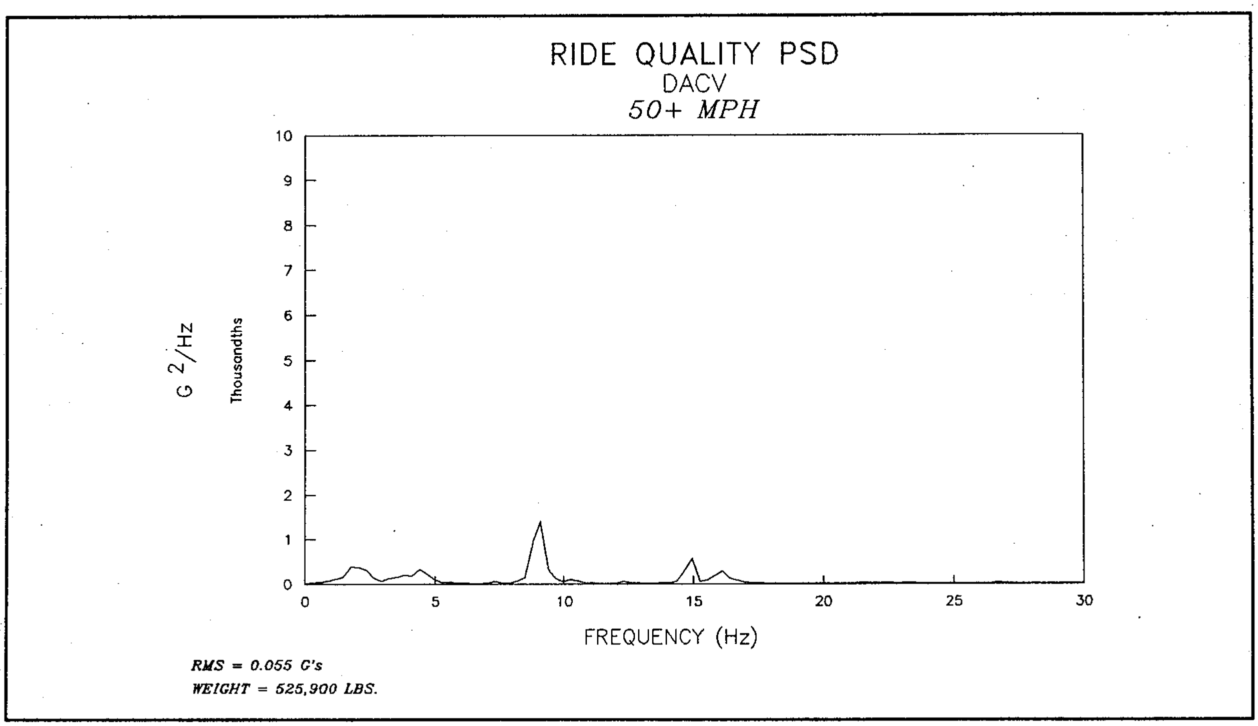


Figure 26. Tank Car A-End Vertical Accelerometer PSD.

The spike at 10.6 Hz seems to be vertical bending. The spike is high at the middle of the tank car and very low at the A-end. The motion would be similar to that pictured in figure 27.

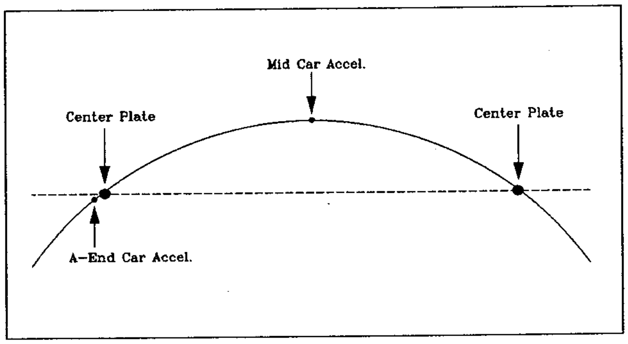


Figure 27. Vertical Bending of the Tank Car.

The center plates do not really move; however, the A-end accelerometer was slightly forward of the center plate, therefore, it saw some vibration. The two accelerometers were out of phase during this mode as shown in figure 27 and as seen in the data. The 10.6 Hz spike also disappeared when the tank car was empty, as shown later.

In comparison, the passenger car saw substantially lower vibration levels and the PSD's showed less frequency content as well.

Figure 28 is a PSD of the middle of the passenger car vertically. The unweighted rms level is much lower than the middle of the tank car, 0.029 G vs. 0.192 G. Only one major spike is seen in the middle of the passenger car. This spike is at approximately 2 Hz. This seems to be a <u>bounce</u> mode as the middle of the car and the A-end of the car are <u>nearly in</u> phase. A similar spike is shown in figure 29, which is the spectrum of the passenger car A-end vertical vibration. The spike is slightly higher than that at the middle of the car. The time slice at which these PSD's were calculated for was the worst ride condition for the passenger car. The test team became quite uncomfortable at this point because the resonant <u>bounce</u> frequency could be felt. It became difficult to stand up, let alone take notes in the log book or operate the computer.

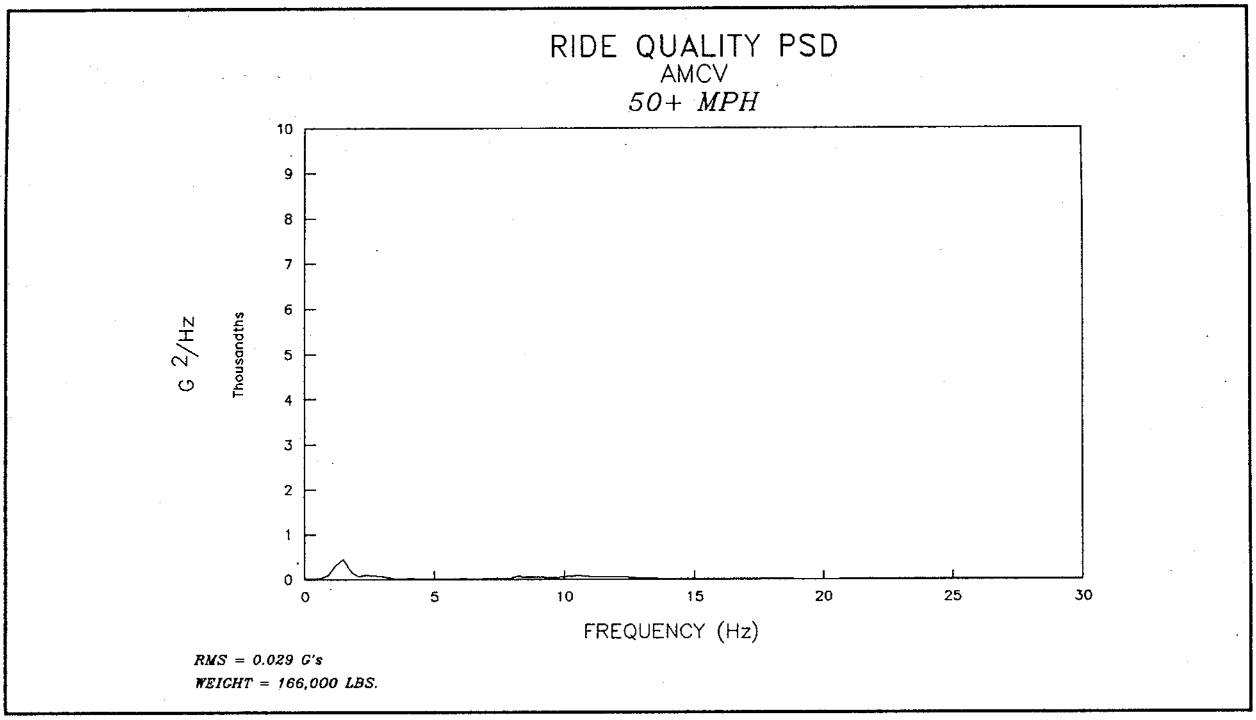


Figure 28. Passenger Car Mid-car Vertical Accelerometer PSD.

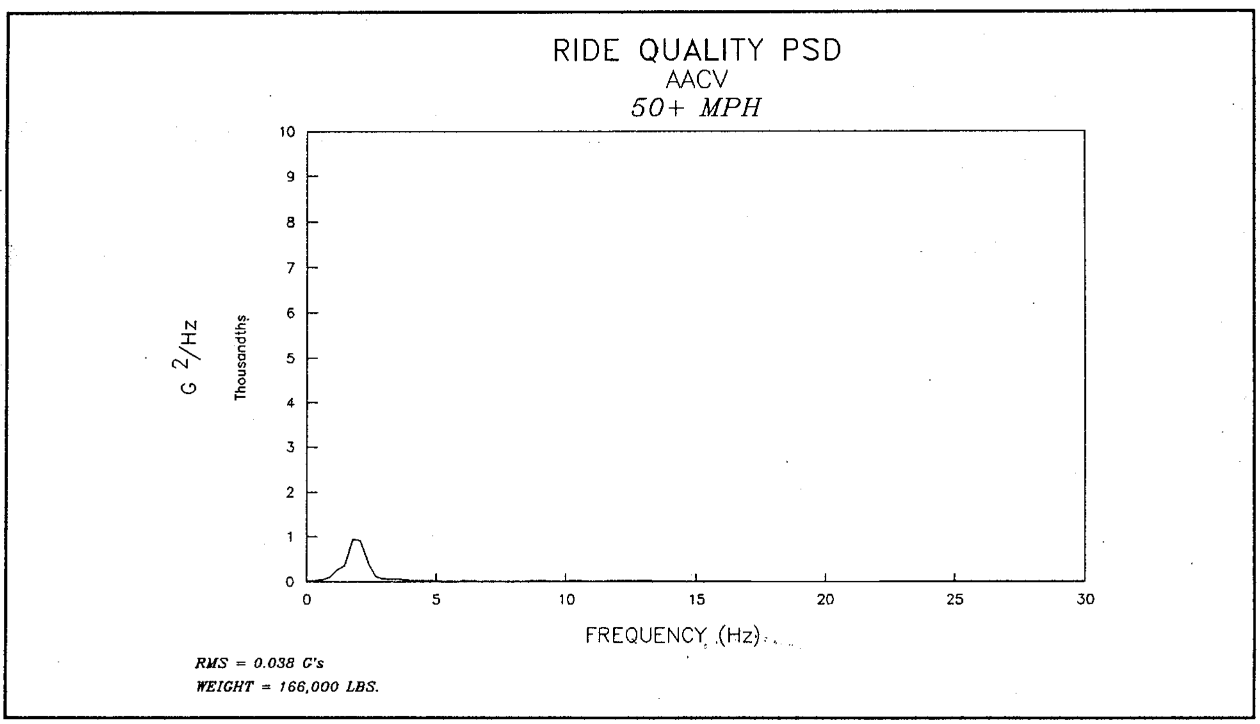


Figure 29. Passenger Car A-End Vertical Accelerometer PSD.

The PSD's from the passenger car look as though the channels were filtered differently than the tank car channels. In a way this is true. The passenger car suspension acted like a mechanical filter. It reduced the severity of the rigid body inputs as well as limited the excitation of the flexible body frequencies.

All channels were filtered at 30 Hz with Pacific two pole (12 dB/octave) filters.

PSD's for each speed category for the loaded portion of the trip are presented in Appendix A.

On the return portion of the trip the tank car was empty. Overall vibration levels were also charted for this empty tank car versus the passenger car in the same manner as the loaded tank car. Figure 30 contains the first chart that shows the vibration levels of the tank car and passenger car in the speed range of 15 - 24 mph. Here one clearly sees that the tank car is already having vibration levels that were close to those at high speeds when it was loaded. The middle of the tank car is at the 1.25 hour limit and the A-end of the tank car is at the 3-hour limit. The passenger car is also having a higher vibration level even though the weight has not changed. The limits range from 5 to 4 hours for the middle and A-end of the car. Even when the tank car is empty the exposure limits are worse than the passenger car.

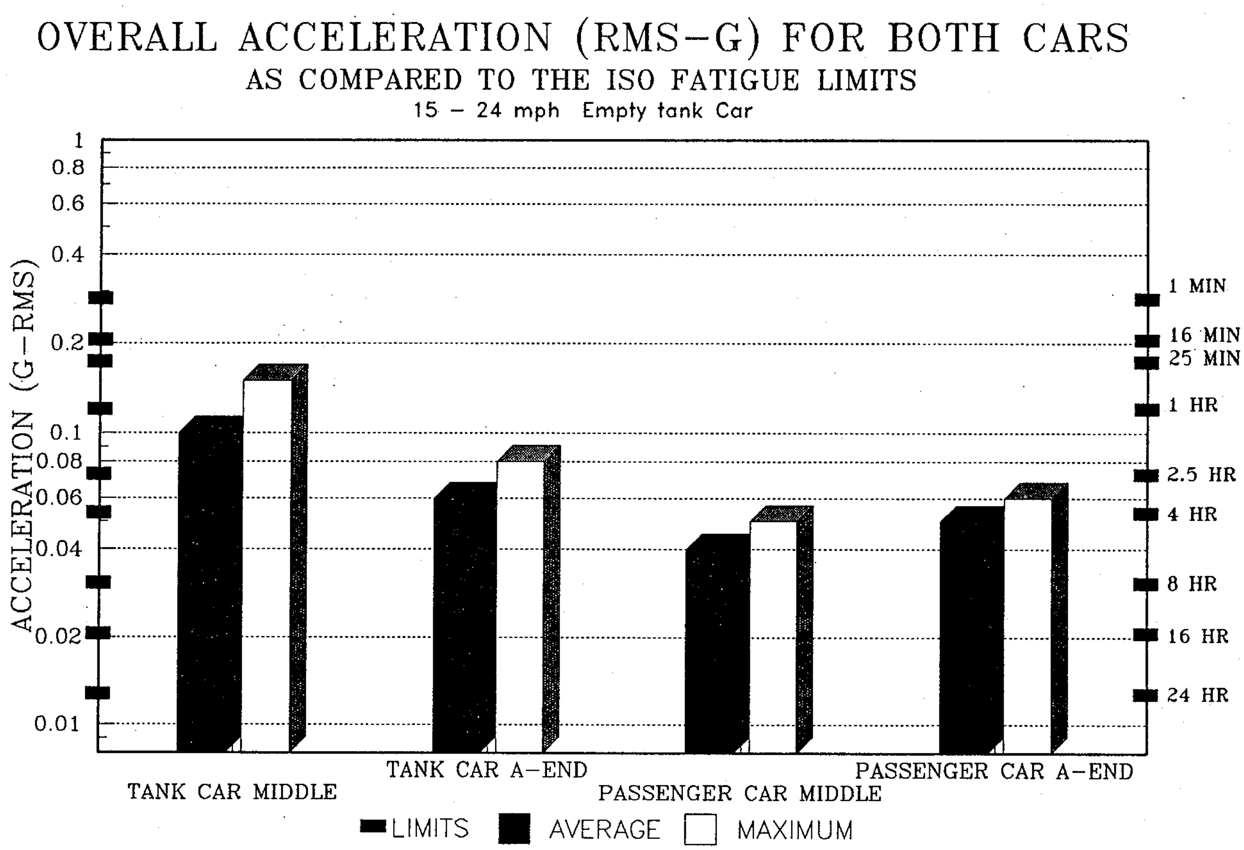


Figure 30. Empty Tank Car 15 - 24 mph Vibration Levels

The second speed range to be charted was 25 - 39 mph (figure 31). Again with the higher speed, the vibration levels increased. The tank car was at the 25 minute and 2.5 hour limit for the middle and A-end, respectively. The passenger car was still in the 5-hour and 4-hour limits for the middle and A-end of the car. So the average vibration levels were again increasing with higher speed.

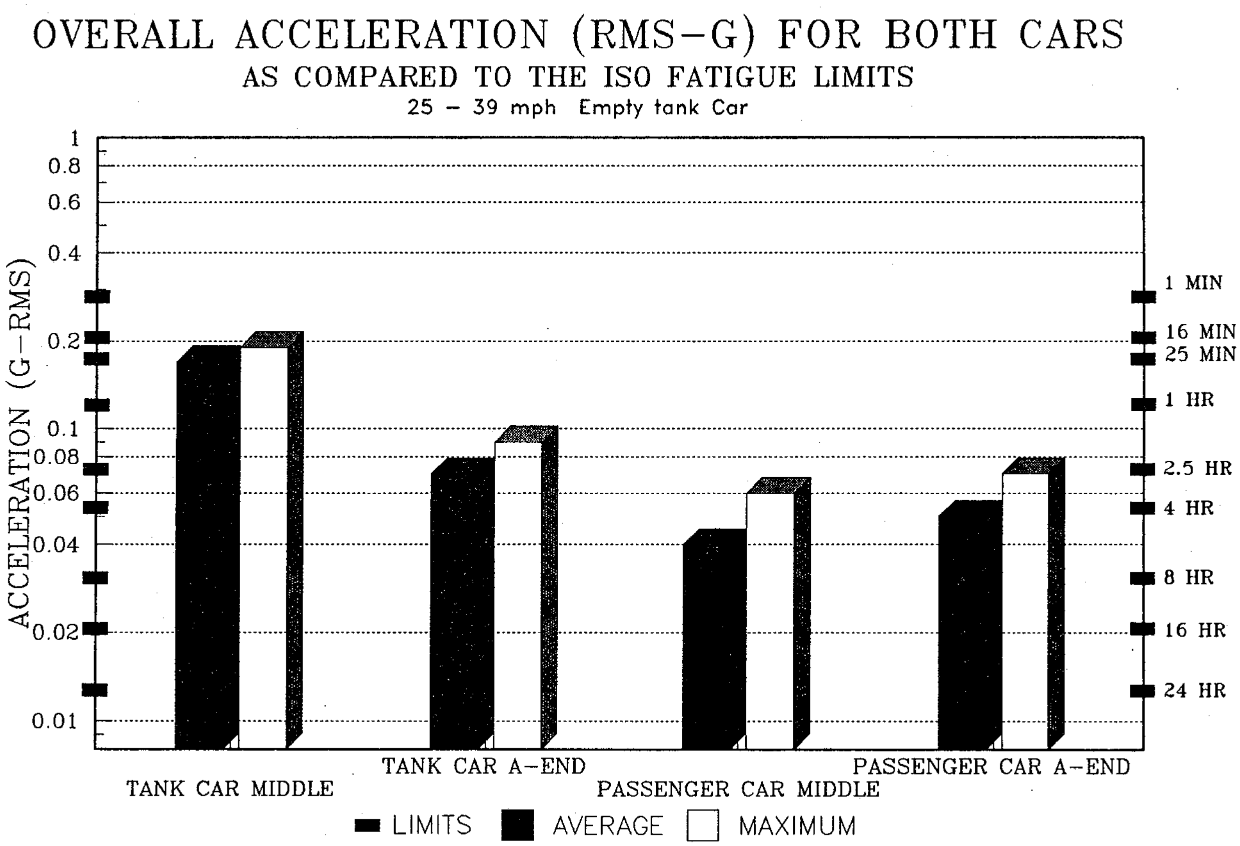


Figure 31. Empty Tank Car 25 - 39 mph Vibration Levels

Third, the 40 - 49 mph speed range was examined. Figure 32 outlines the comparison of the two cars. The tank car limits were slightly different than the 25 - 39 mph range, with limits of 30 minutes and 2 hours for the middle and A-end of the car. The middle of the passenger car did not change from the 5-hour limit; however, the A-end increased to a 3-hour limit. The passenger car was starting to be subjected to a higher vibration level at a higher speed.

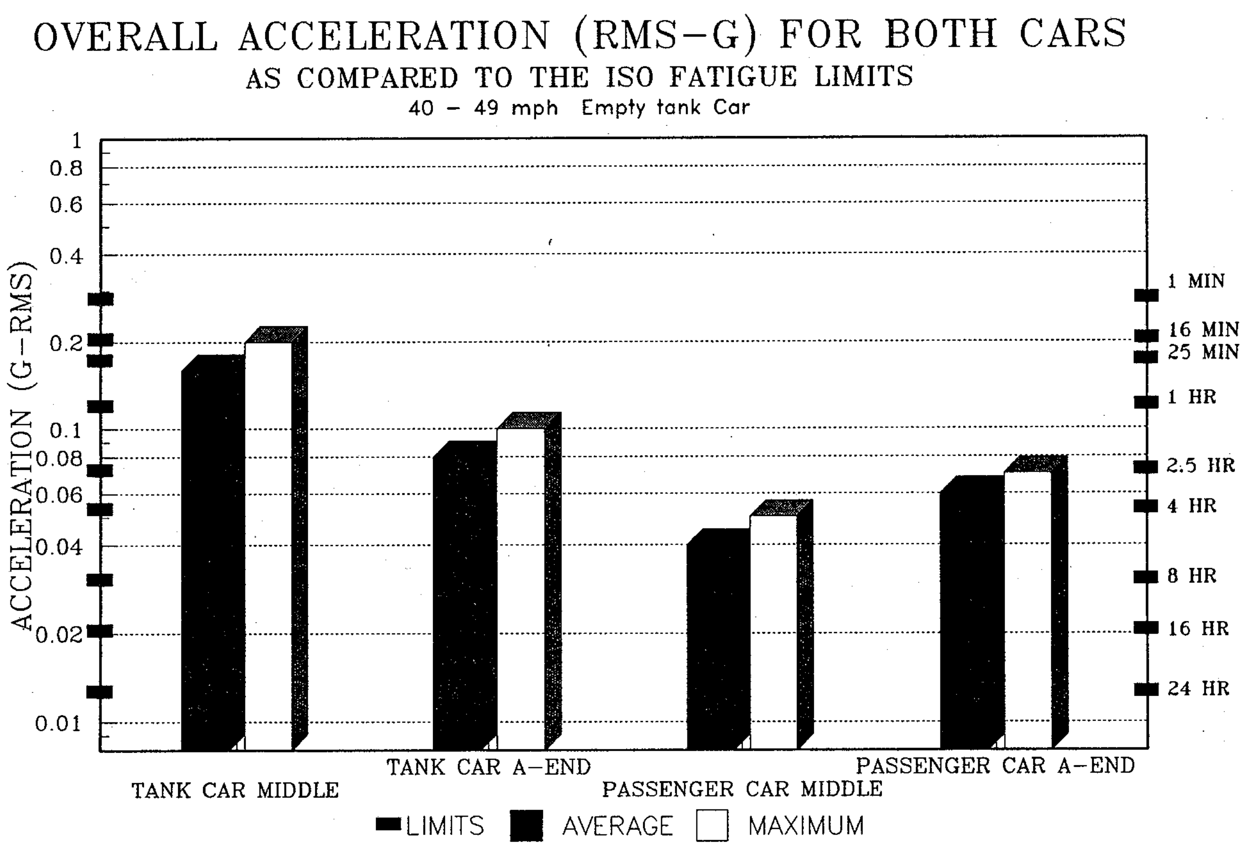


Figure 32. Empty Tank Car 40 - 49 mph Vibration Levels

The last speed range to investigate is the 50+ mph. Figure 33 contains this data. Here the tank car received the highest vibration levels. The limits were 20 minutes and 1.75 hours for the middle and A-end of the car. The passenger car also encountered the highest vibration seen. The limits were 4 and 3 hours for the middle and A-end, respectively.

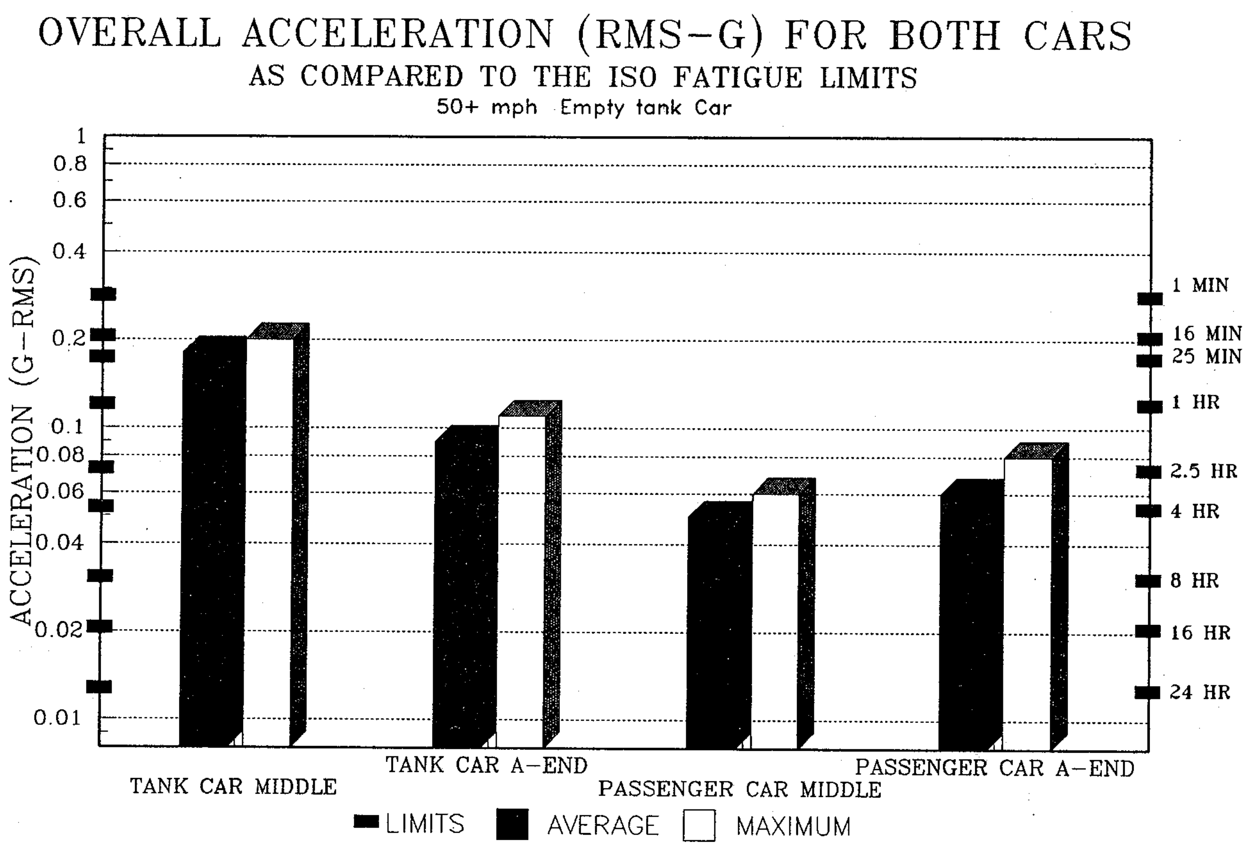


Figure 33. Empty Tank Car 50+ mph Vibration Levels

Next are two PSD's that are the vertical accelerometer over the A-end truck of each car: the empty tank car and the passenger car. The tank car received flats on all of the wheels before the return trip started. Figure 34 shows a picture of a flat on one of the tank car wheels. Figure 35 is the PSD of the empty tank car A-end vertical accelerometer when the speed was greater than 50 mph. This PSD shows a spike near 9 Hz, which may be attributed to the wheel flats. Should a Rail Garrison car ever receive a wheel flat, a PSD similar to figure 35 could be seen. The PSD on the passenger car shows a distinct spike near 2 Hz (figure 36). This would be the rigid body bounce frequency of the passenger car. It can also be seen that the overall PSD is much smoother than the tank car, which is again due to the suspension of the passenger car filtering out more vibration than the tank car suspension.

Figure 37 shows the vertical vibration spectrum for the middle of the tank car. The vertical bending frequency shifted from 10.6 Hz, as noted in figure 25 for the loaded tank car, to 12.5 Hz. The 4-8 Hz ISO filter would still allow much of the 12.5 Hz data to contribute to the overall rms level. The peak corresponds to 0.013 g^2/Hz in figure 37 for the empty tank car as opposed to 0.005 g^2/Hz for the loaded tank car. This would indicate that the loaded tank car had better damping, either due to the suspension system being more compressed than for the empty tank car or the ethelyne glycol. All of the PSD's for every channel on the empty tank car portion of the trip are given in Appendix B.

Figure 34. Flat on the Tank Car Wheel

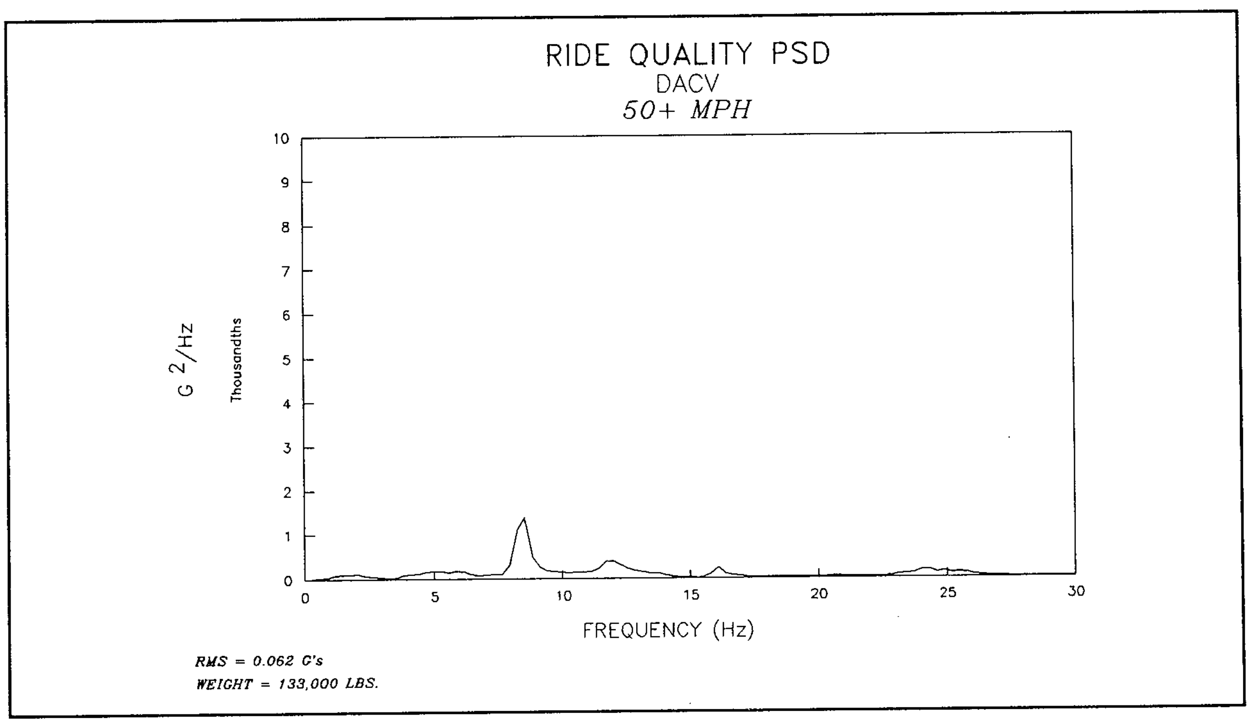


Figure 35. Tank Car A-end Vertical Accelerometer PSD.

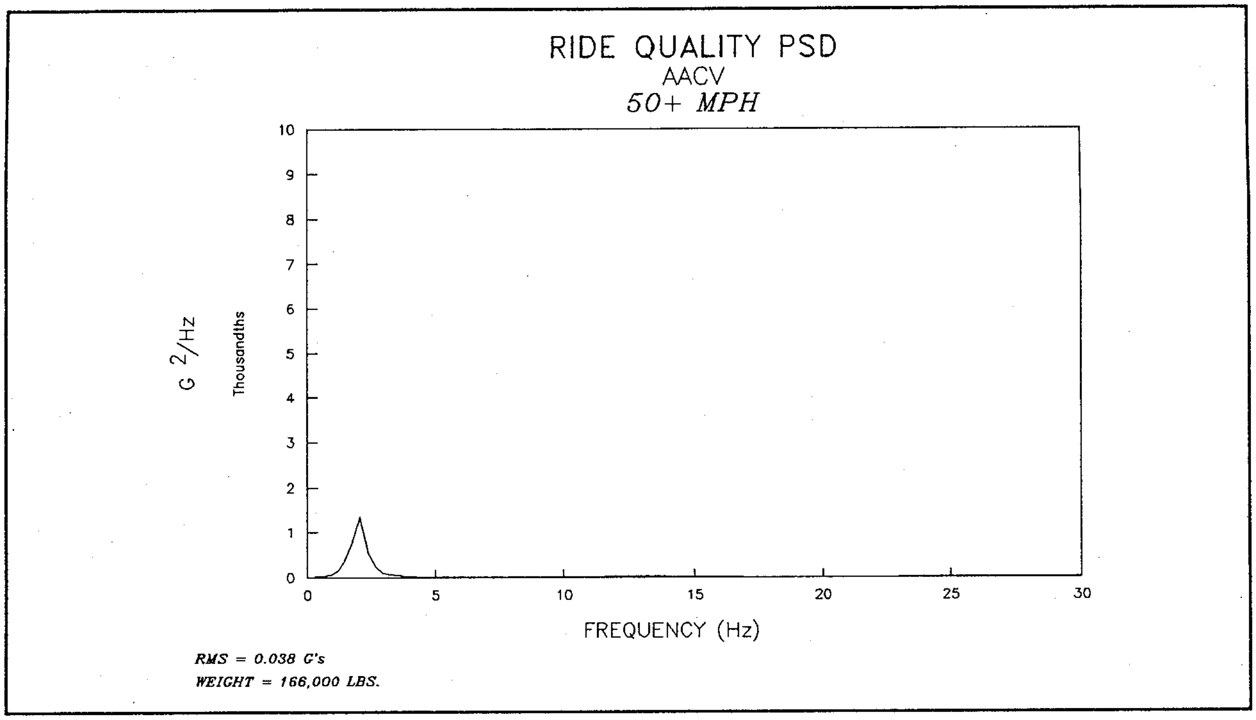


Figure 36. Passenger Car A-end Vertical Accelerometer PSD.

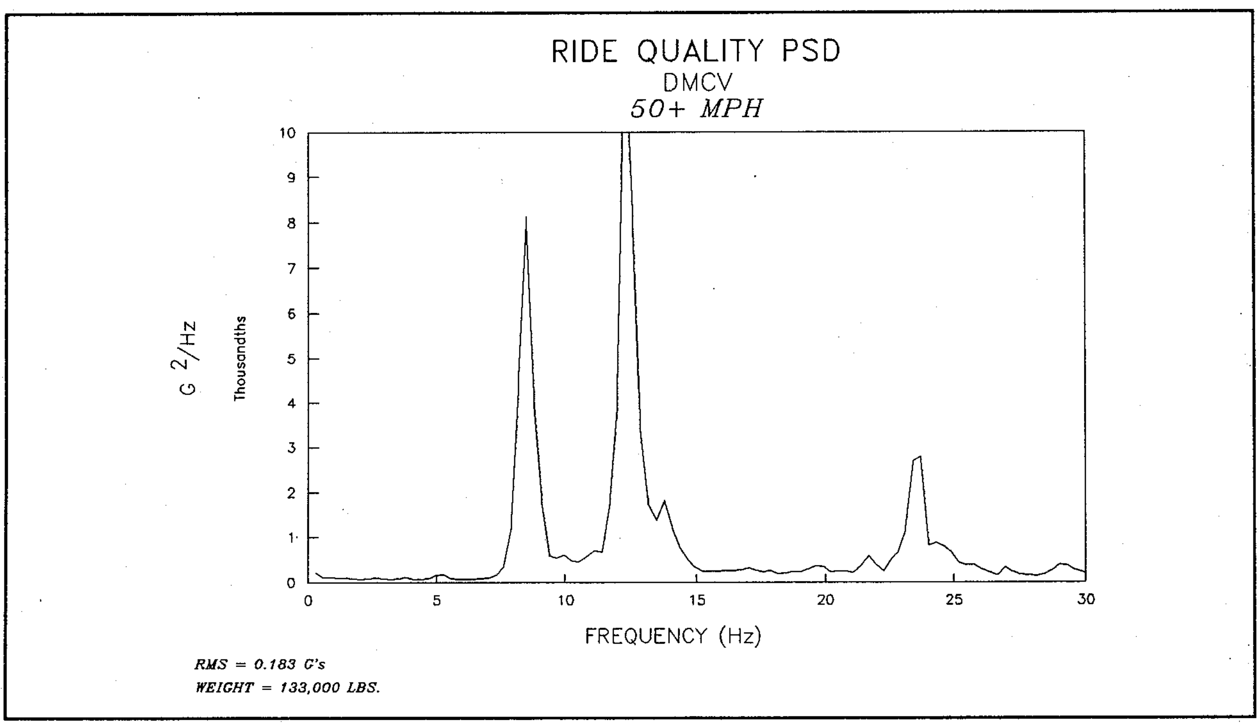


Figure 37. Tank Car Mid-car Vertical Accelerometer PSD.

5.2 HIGH FREQUENCY DATA

National Technical Systems (NTS) performed the analysis on all of the data that was collected for high frequency (150 to 2000 Hz). The conclusions stated in this section are from the final report from NTS, which is included in Appendix D. Most of the data analyzed by NTS was hand-smoothed, one-third octave band and hand-smoothed, power spectral densities (PSD). NTS analysis was performed only for the loaded DUPX tank car.

At the request of NTS, 500 g piezoelectric accelerometers were used for all high frequency measurements. The scaling factor for the vertical accelerometers was 10 millivolts/g. The scaling factor for the lateral and longitudinal accelerometers was 100 mV/g. The HP6944A multiprogrammer had a resolution of 5 mV/count and an accuracy of ± 1 count. This corresponds to an accuracy of ± 1.0 g vertical and ± 0.10 g lateral and longitudinal.

A similar situation was also found in "Preliminary Vibration Measurements on R-42 Vehicle" published by the Transportation Systems Center in 1971. [2]

Assuming that the axle motion measured by the high frequency accelerometers is representative of rail roughness, the measured data above 150 Hz satisfactorily substantiates the rail roughness PSD in the weapon system vibration specification. [3] One important factor from the NTS investigation is the response of the span bolster. Given that the trucks, span bolster, dimensions and weights of the DUPX tank car are representative of the PRG cars, the span bolster data may be a good estimator of the vibration environments introduced into the PRG car bodies. The span bolster had very small longitudinal motion compared to the vertical and lateral motions, except during coupling or run-in situations. This may be important with vibration sensitive equipment, which could be oriented to take advantage of this apparent response. Two accelerometers were also mounted on the car body at the middle of the tank

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2 Transportation Systems Center, "Preliminary Vibration Measurements on R-42 Vehicle," Report No. DOT-TSC-UMTA-72-2, October 1971.

3 Peacekeeper Rail Garrison, "Weapon System Specification, S-118-500-30," 1 November 1988.

car. The high frequency vibrations were transmitted from the span bolster to the car body unaltered, or at best with only a small degree of attenuation. The eight accelerometer locations and names are listed in Table 6.

Table 6.
High Frequency Accelerometers

Channel Name	Type	Location
HF1	PCB Piezoelectric	DUPX, span bolster, center, vertical
HF2	PCB Piezoelectric	DUPX, span bolster, center, lateral
HF3	PCB Piezoelectric	DUPX, span bolster, center, longitudinal
HF4	PCB Piezoelectric	DUPX, car body, center line, center of car, vertical
HF5	PCB Piezoelectric	DUPX, car body, center line, center of car, lateral
HF6	PCB Piezoelectric	DUPX, axle 1, right, vertical
HF7	PCB Piezoelectric	DUPX, axle 1, left, vertical
HF8	PCB Piezoelectric	DUPX, axle 1, left, lateral

6.0 CONCLUSIONS

1. The tank car, with span bolsters and freight trucks, had higher vibration levels than the passenger car, with passenger car trucks, for the low frequency environment. This was definitely due to the difference in suspension. The high vibration levels were due mainly to wheel related input and the first vertical bending mode. It was clear that the passenger car suspension damped out "road noise" and inputs which would excite the bending modes.

2. The tank car vibration levels increased as the speed increased. This was due, primarily, to the road noise, and also due to the higher energy inputs exciting the first bending mode.

3. The loaded tank car fatigue and decreased proficiency limits were as low as 1.5 hours. For the middle and A-end of the car and for all speed ranges, the limits ranged from 1.5 hours to 16 hours with an average of approximately 6 hours. This will definitely affect the performance of a Rail Garrison crew working an 8 hour shift.

4. The empty tank car vibration levels were higher than the loaded tank car vibration levels. This was primarily due to the wheel flats received en route contributing to an increase in road noise and the light damping of the 12.5 Hz vertical bending frequency.

5. The flexible body bending frequency of the empty tank car was higher than the loaded tank car flexible body bending frequency. This would be expected. The

Launch Control Car (LCC), being lighter than the tank car, may have a higher bending frequency. That bending frequency may not affect ride quality due to the ISO weighting factor.

6. The empty tank car had fatigue and decreased proficiency limits as low as 25 minutes, with an average being less than one hour over all speed ranges.

7. The suspension and body characteristics were both factors in the ride quality. Bending frequencies played a larger role than expected. It was anticipated that the rigid body modes would dominate, this was true for the passenger car.

8. The NTS Vibration Investigation Final Report (Ref. 1) concludes that the DUPX vibration data corroborates the applicability of the weapon system vibration specification.

7.0 RECOMMENDATIONS

1. Ride Quality tests should be performed for the LCC and the Security Car (SC). Before testing those cars, modal response tests should be performed so that rigid and flexible body modes may easily be separated from track input.

   It seems clear that no major changes will be made to the LCC and SC suspensions or car body; thus, the mass simulator cars may be suitable for a good preliminary analysis. The PRG consist test would be an excellent time for these ride quality tests.

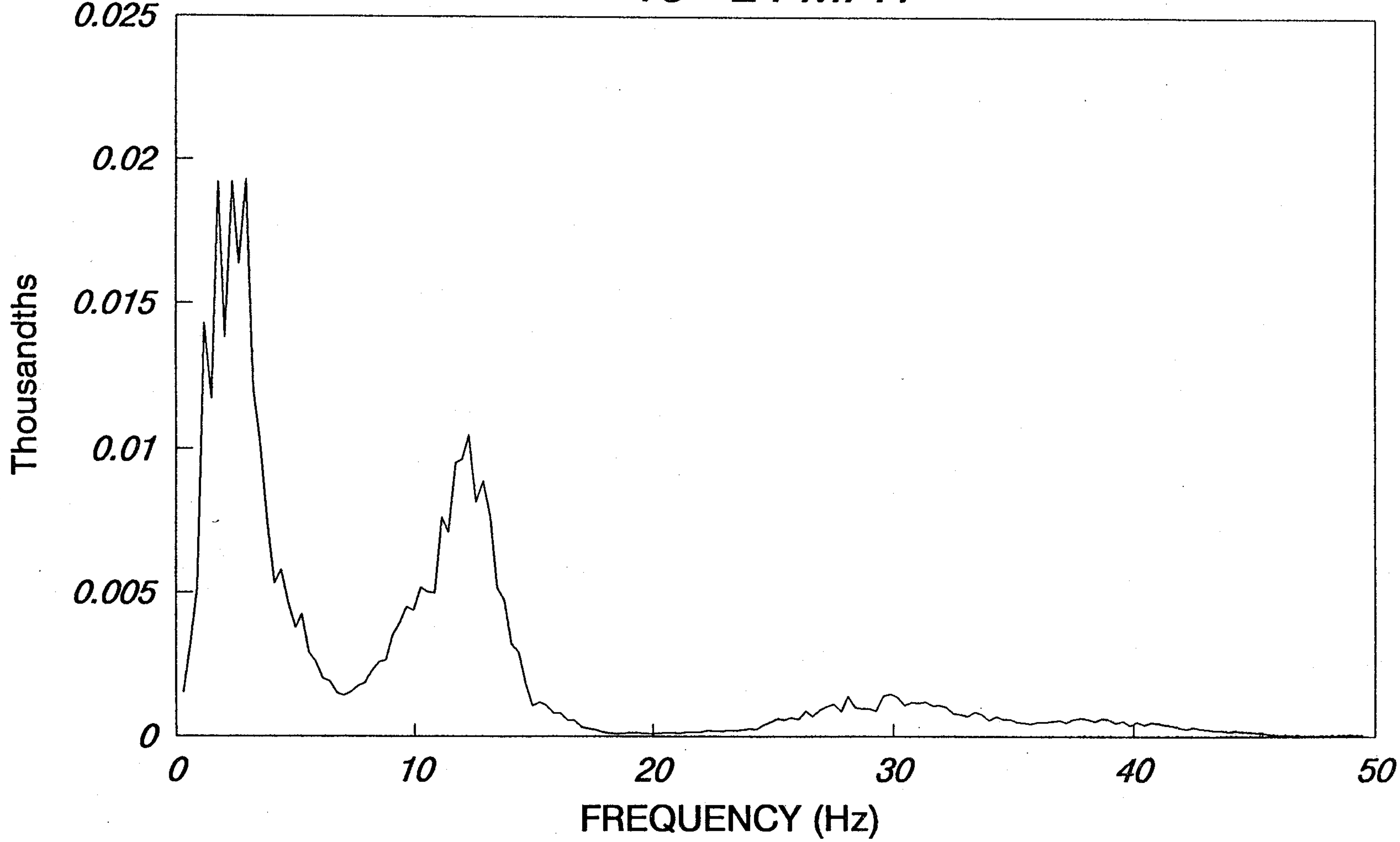
2. Rail Garrison operating procedures may need to be adjusted to allow crews to recover from the environment. Just because the person is not working does not mean that they are not being exposed to the vibration. They need to be removed from the car, or the actual shift length may have to be as low as four hours. The lack of windows may also affect crew performance. The test crew found it easy to become disoriented while traveling in the dark. At times, the test crew could not tell which direction they were traveling; thus, they could not react to things like run-in very well. The combination of high vibration levels and no visual reference point may prove to be a real problem.

3. A test may be performed to determine crew response to such an environment. A boxcar fitted for a PRG crew could be placed on the Simuloader or Vibration Test Unit at TTC. A vibration tape could be played for a designated track or car body vibration and crew response could be monitored.

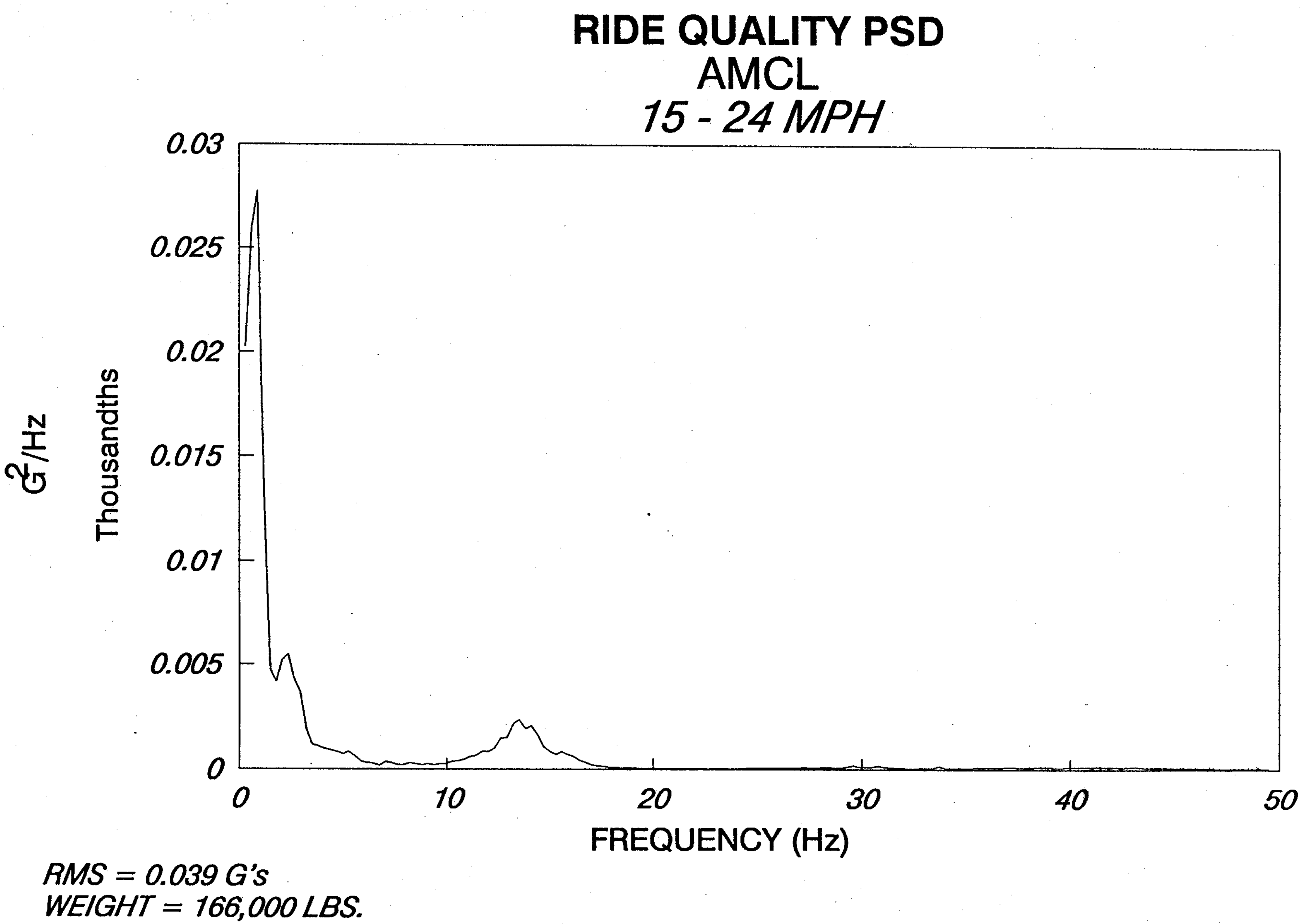
Appendix A

Loaded Tank Car and Passenger Car PSD

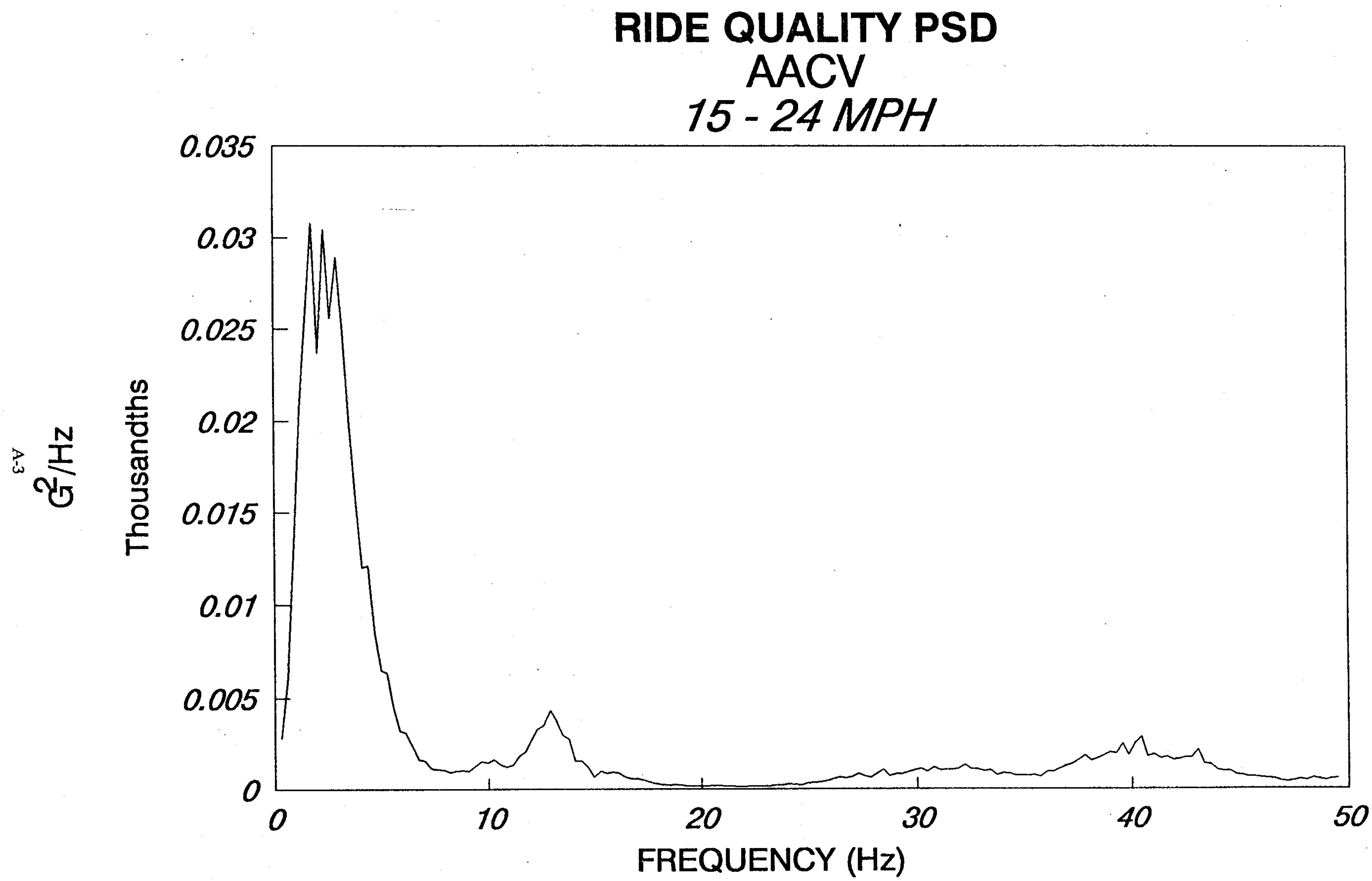
RIDE QUALITY PSD
AMCV
15 - 24 MPH



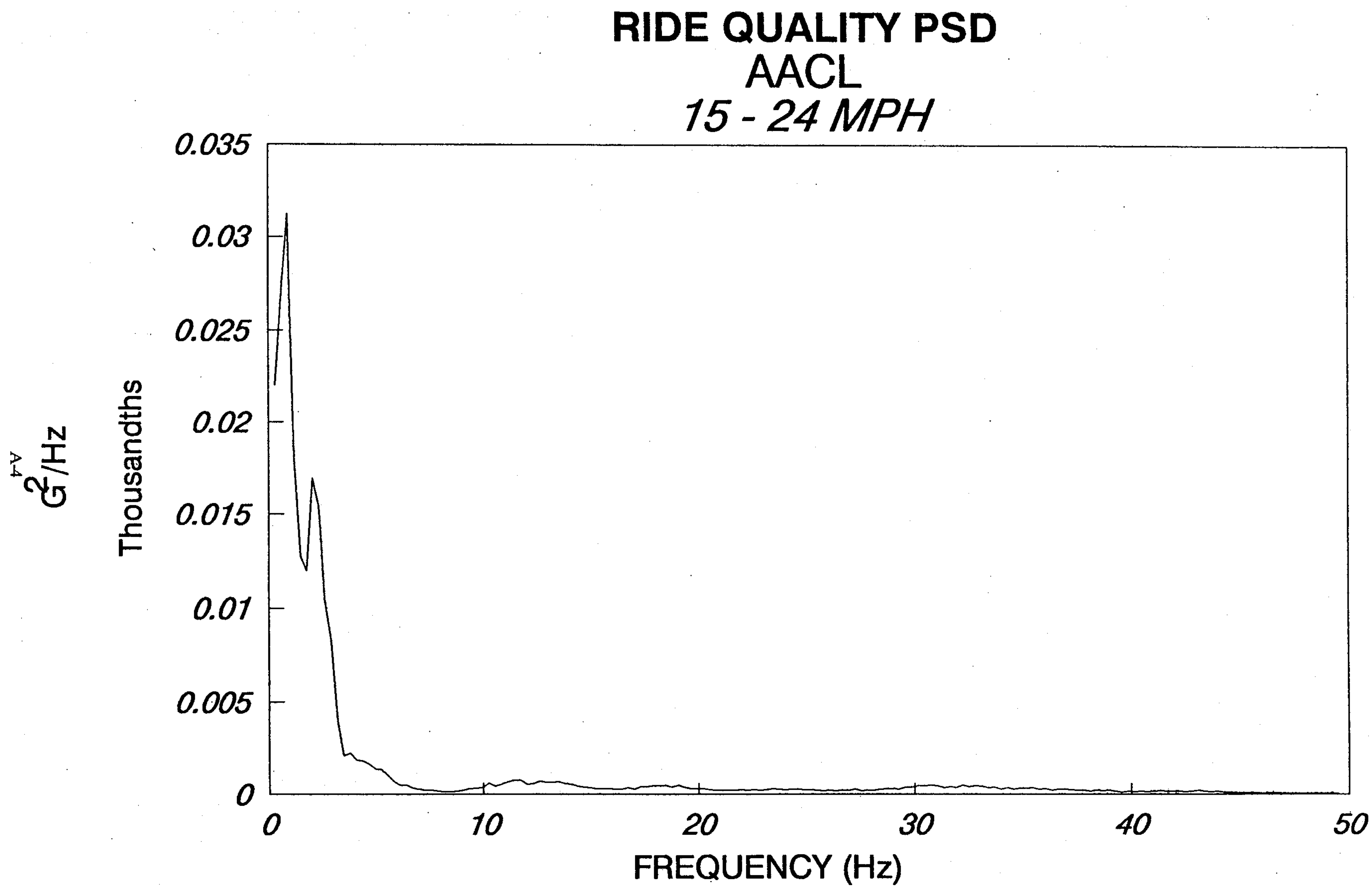
RMS = 0.014 G's
WEIGHT = 166,000 LBS.



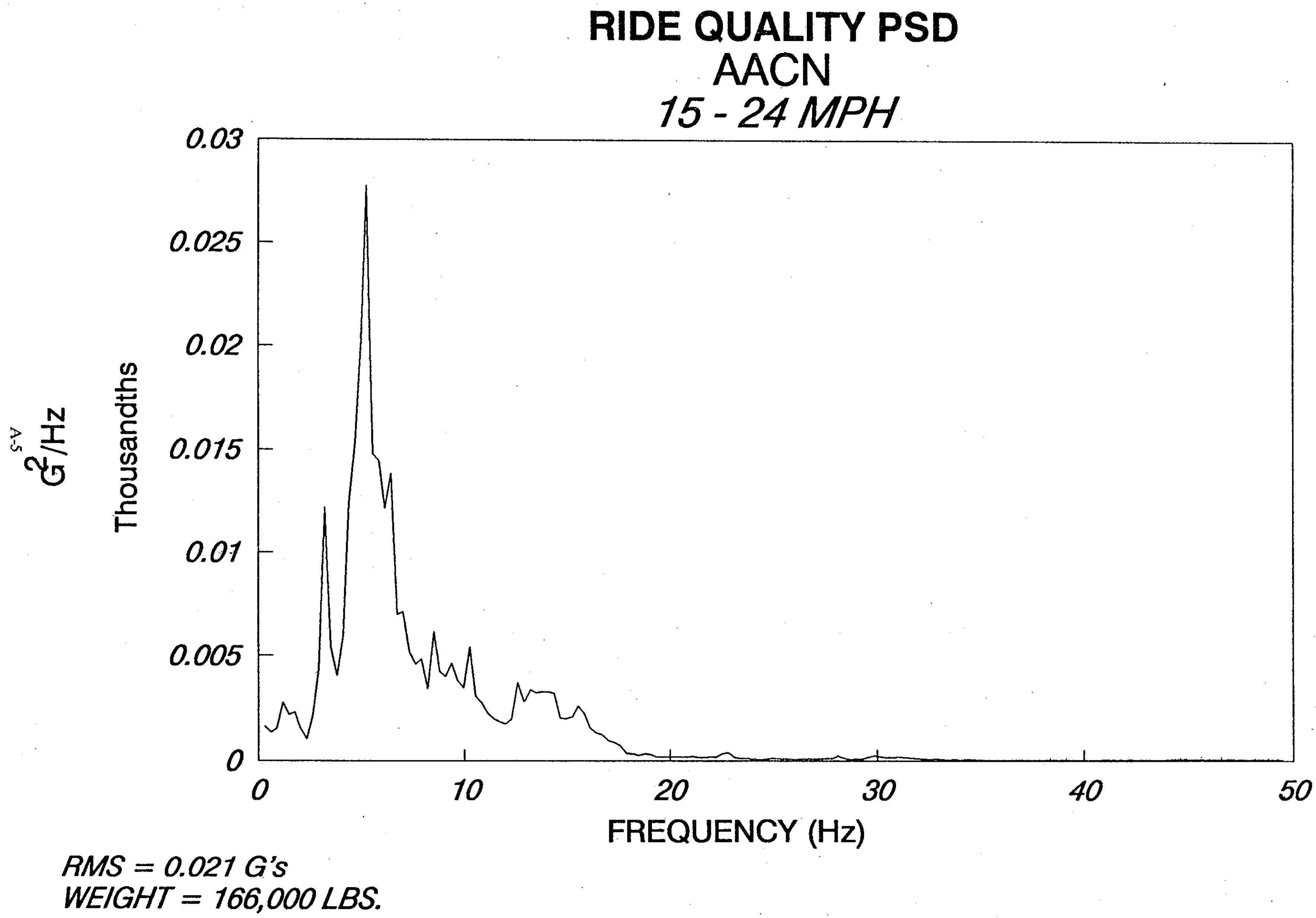
RIDE QUALITY PSD
AMCL
15 - 24 MPH
G²/Hz
Thousandths
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.039 G's
WEIGHT = 166,000 LBS.



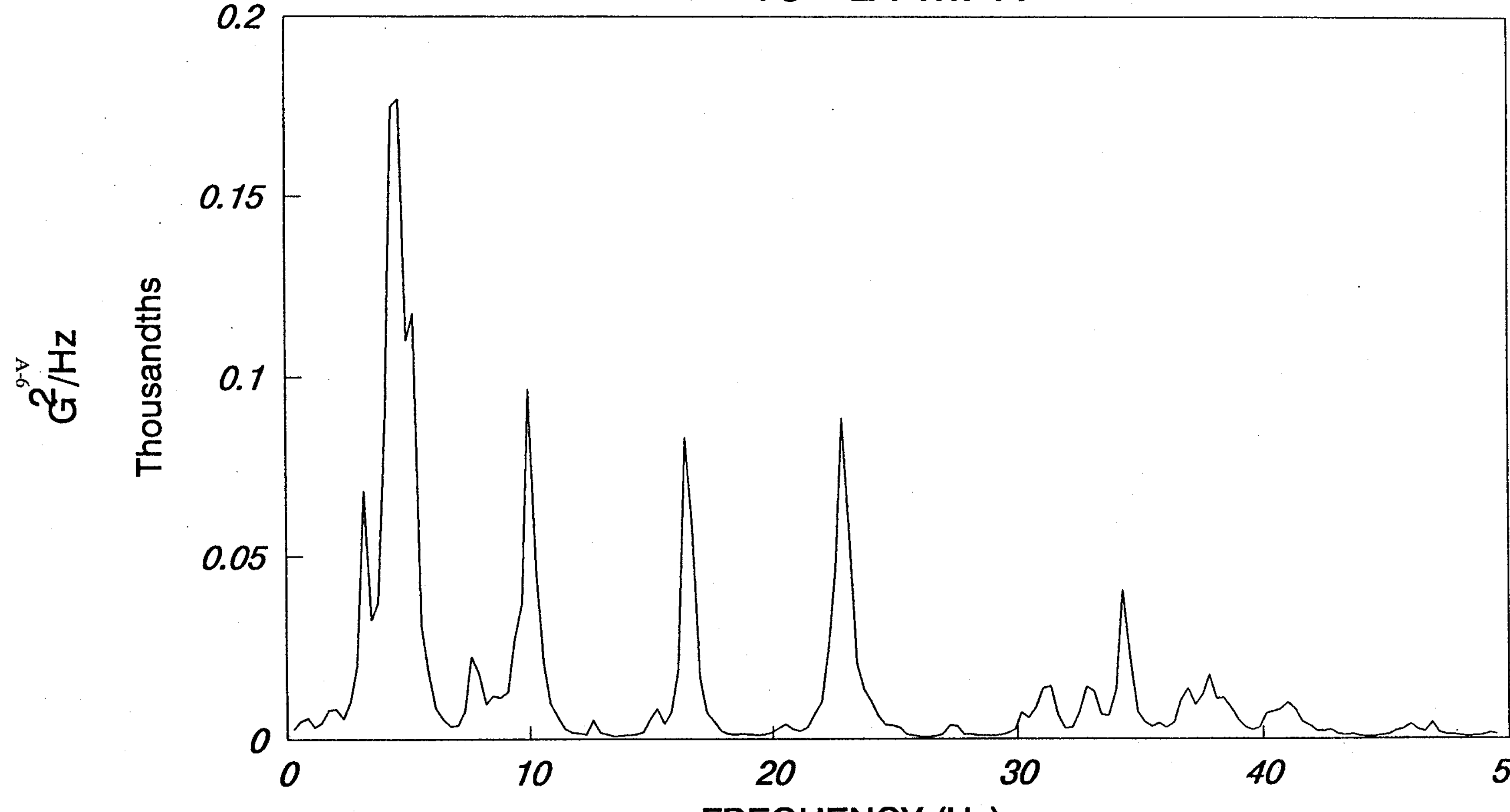
RMS = 0.014 G's
WEIGHT = 166,000 LBS.



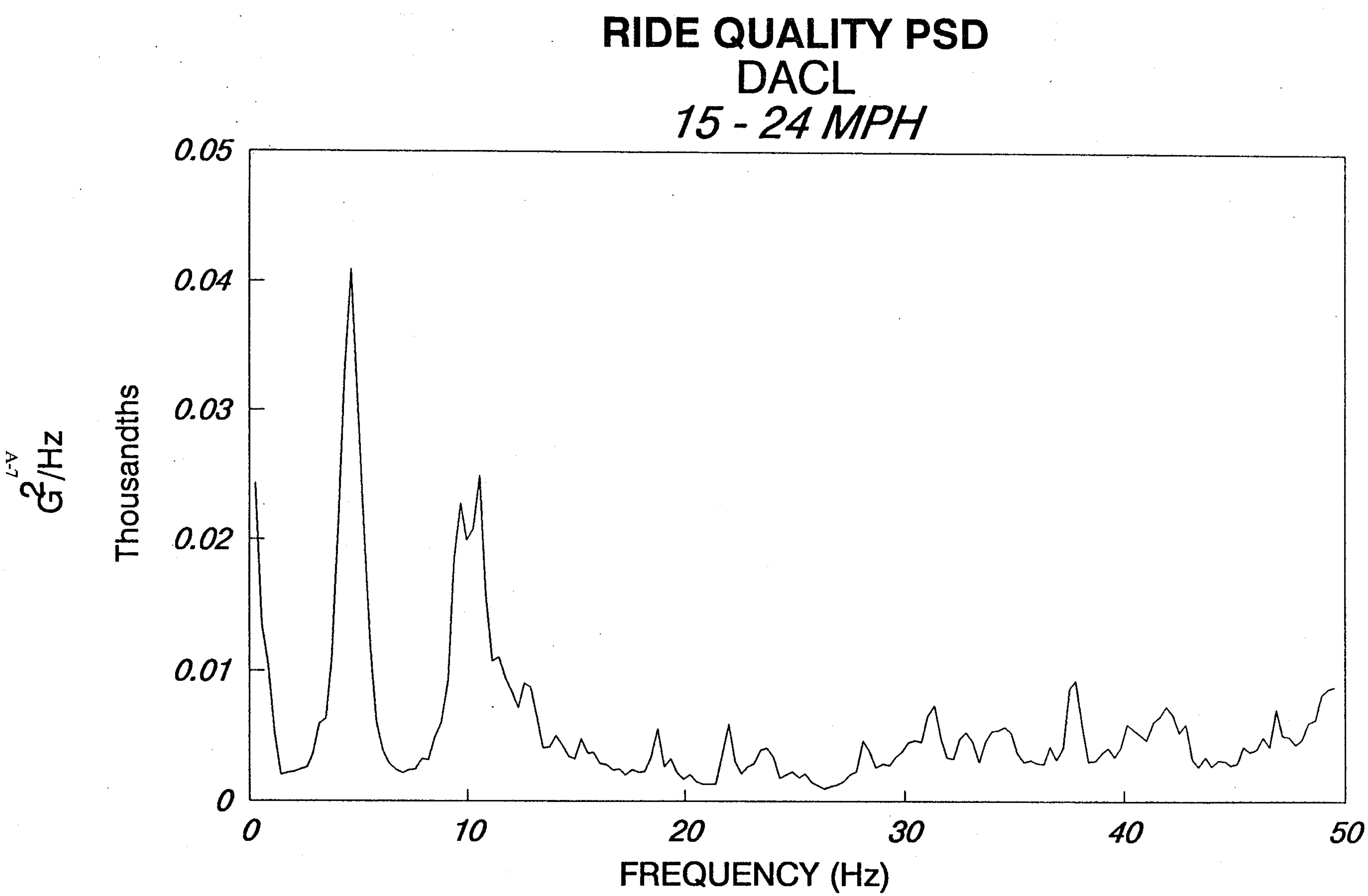
RMS = 0.042 G's
WEIGHT = 166,000 LBS.


RIDE QUALITY PSD
AACN
15 - 24 MPH
G²/Hz
Thousandths
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.021 G's
WEIGHT = 166,000 LBS.

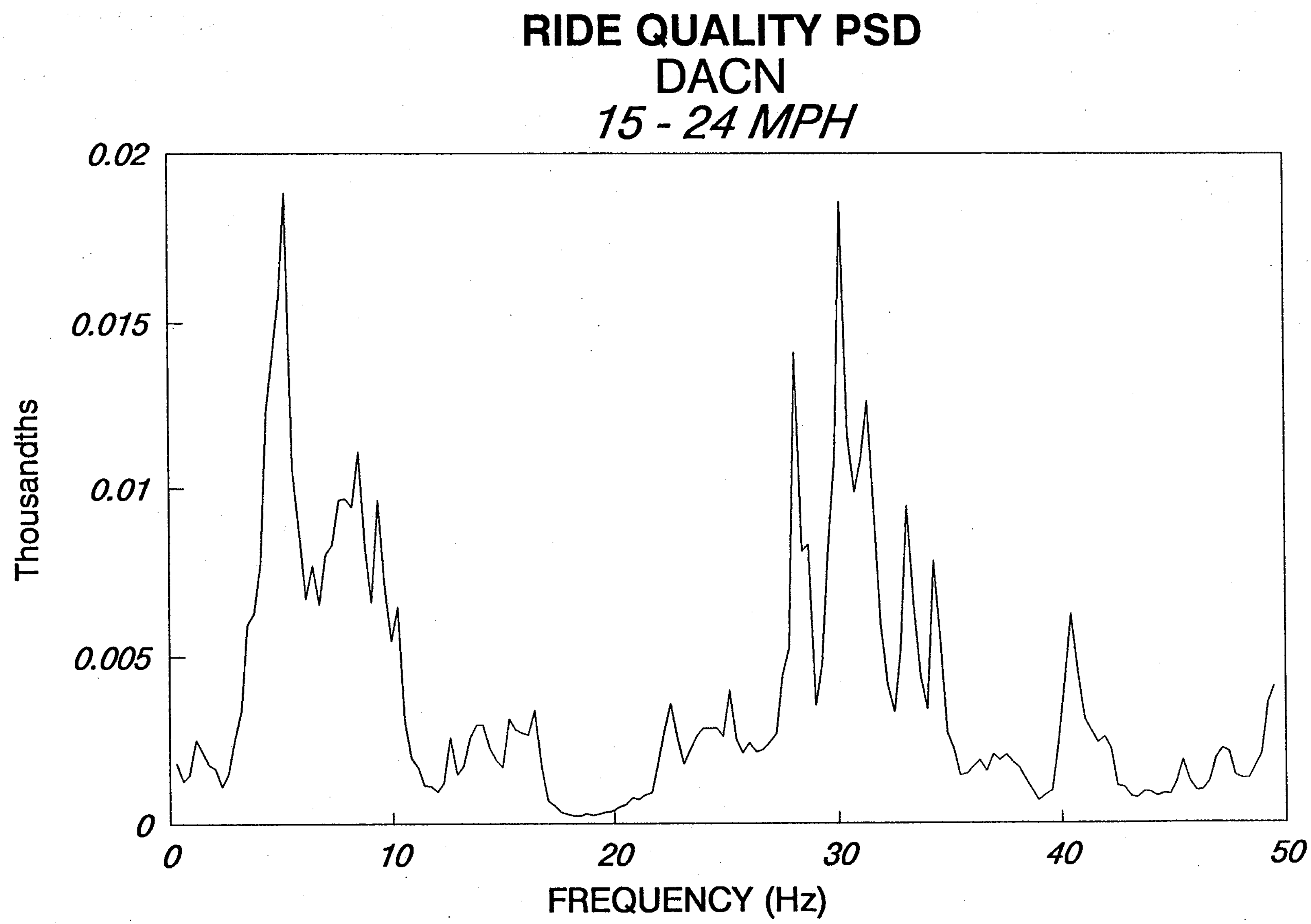
RIDE QUALITY PSD
DACV
15 - 24 MPH



RMS = 0.026 G's
WEIGHT = 525,900 LBS.

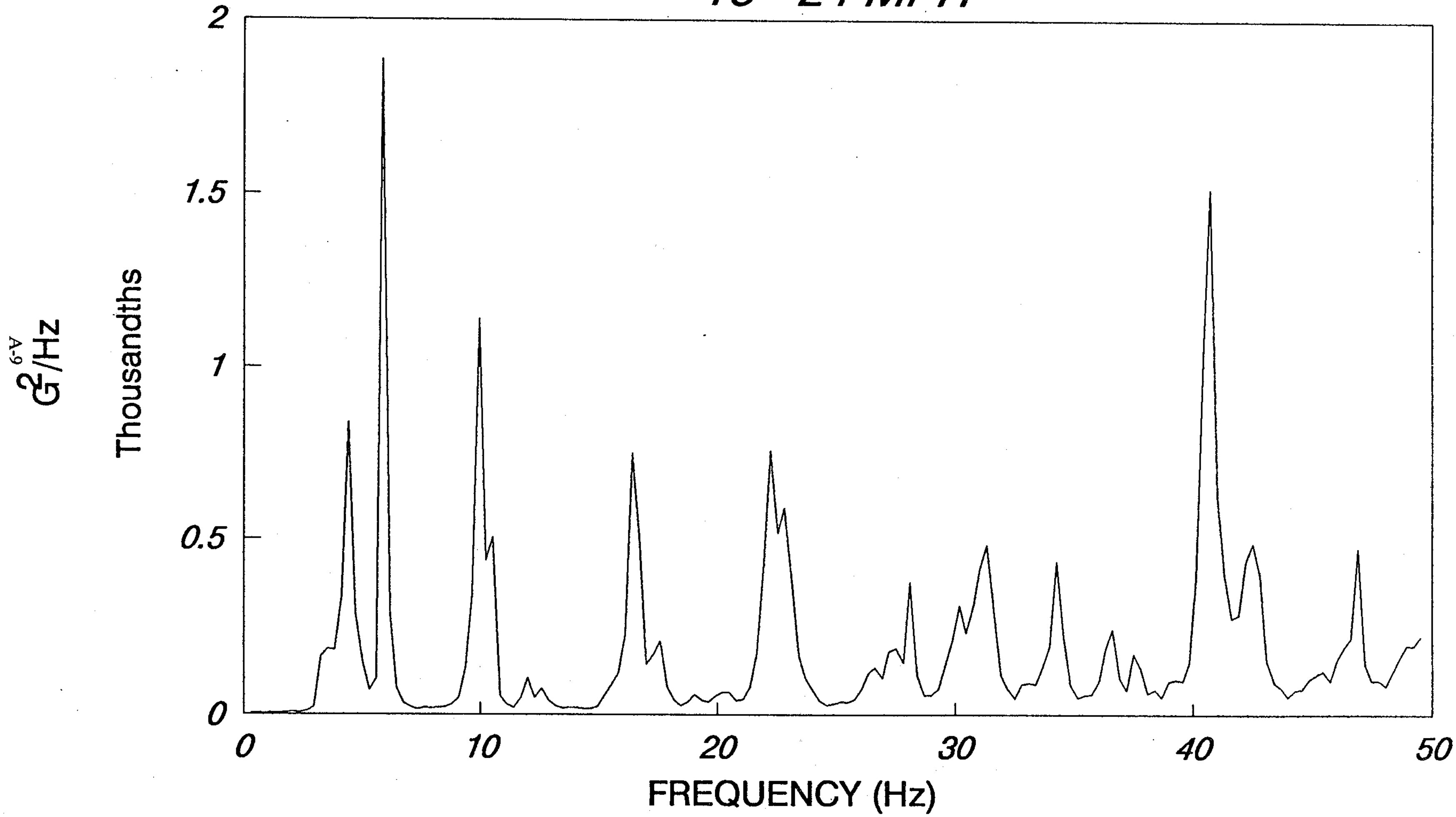


RMS = 0.042 G's
WEIGHT = 525,900 LBS.

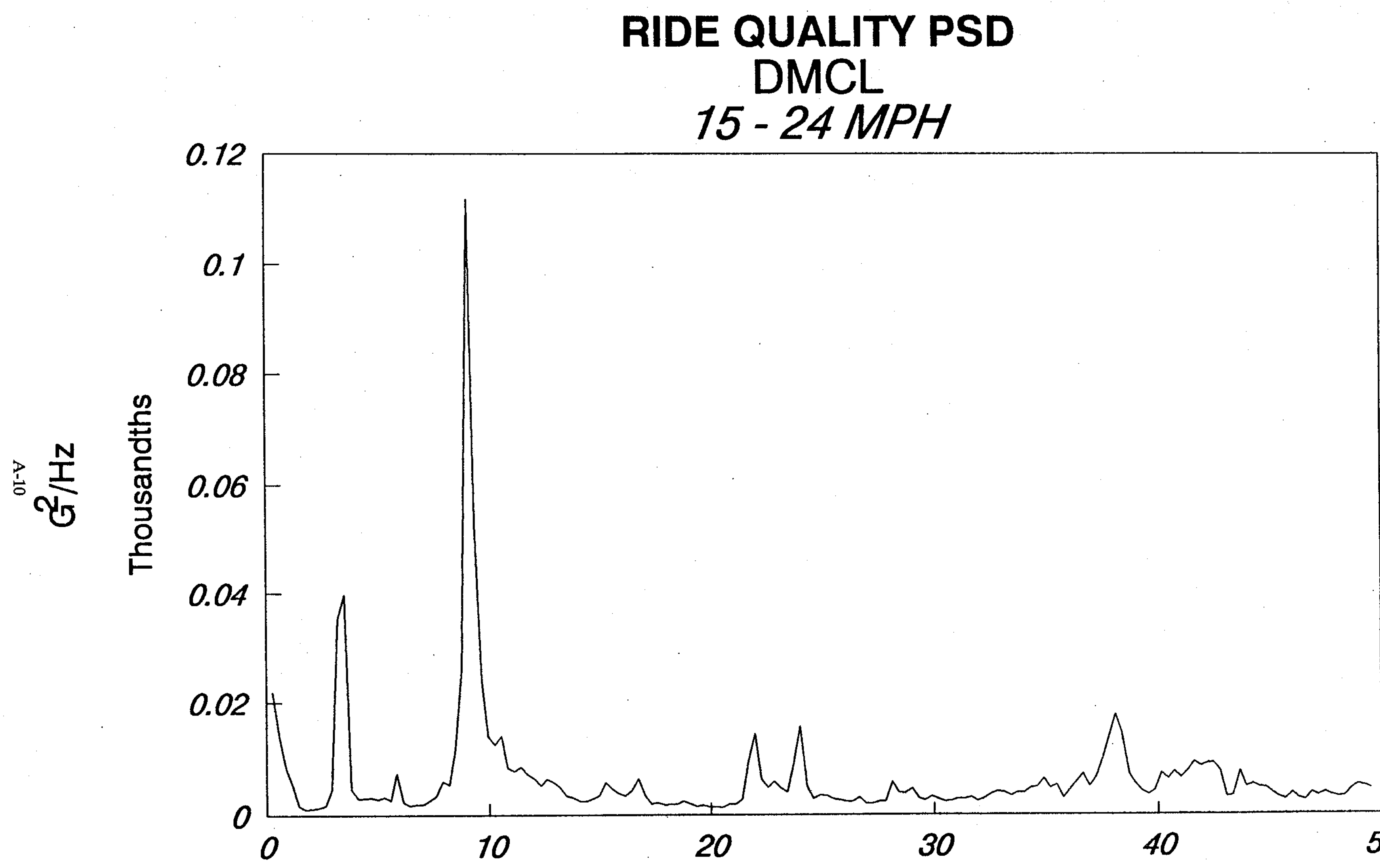


RMS = 0.027 G's
WEIGHT = 525,900 LBS.

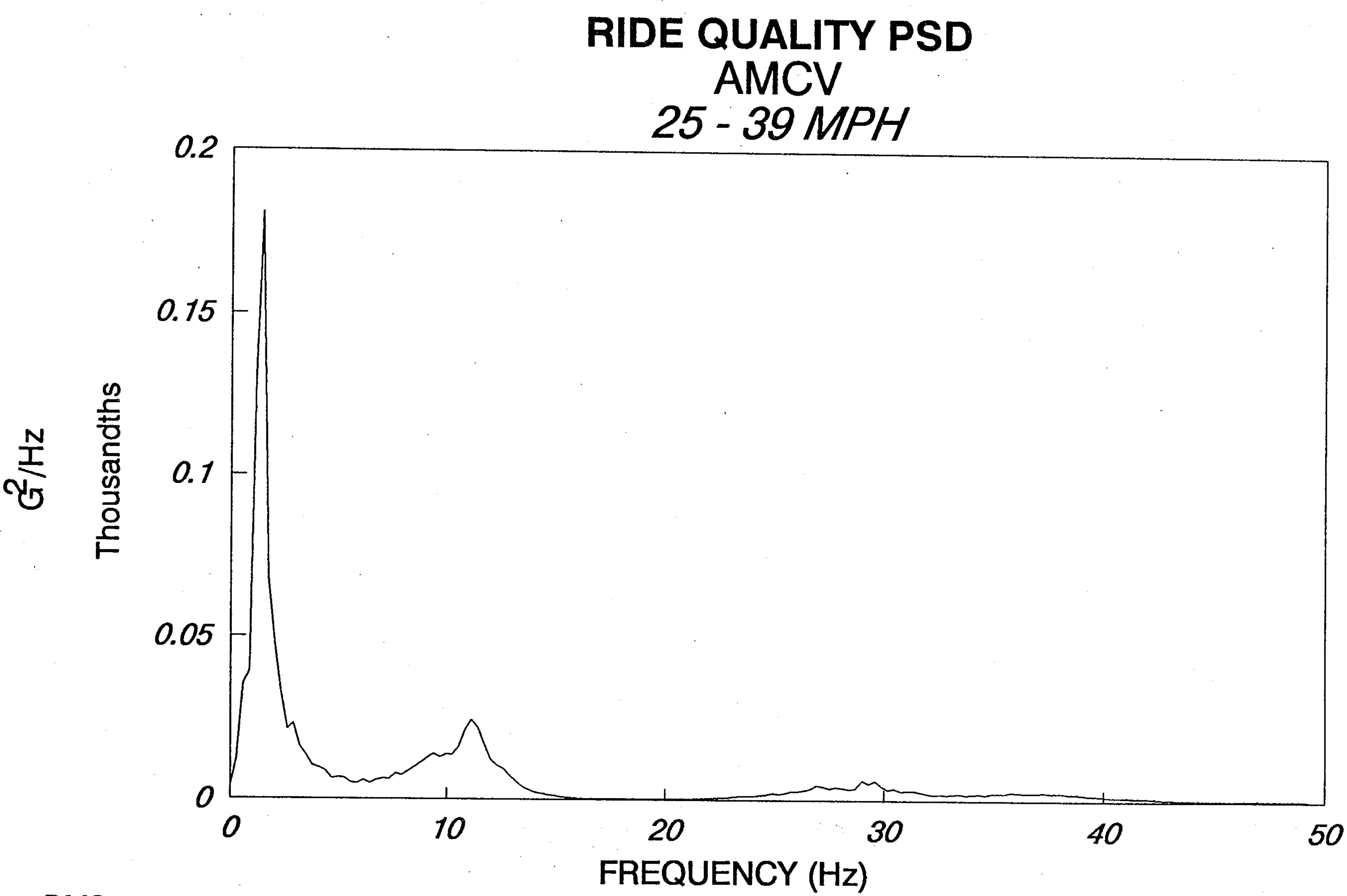
RIDE QUALITY PSD
DMCV
15 - 24 MPH



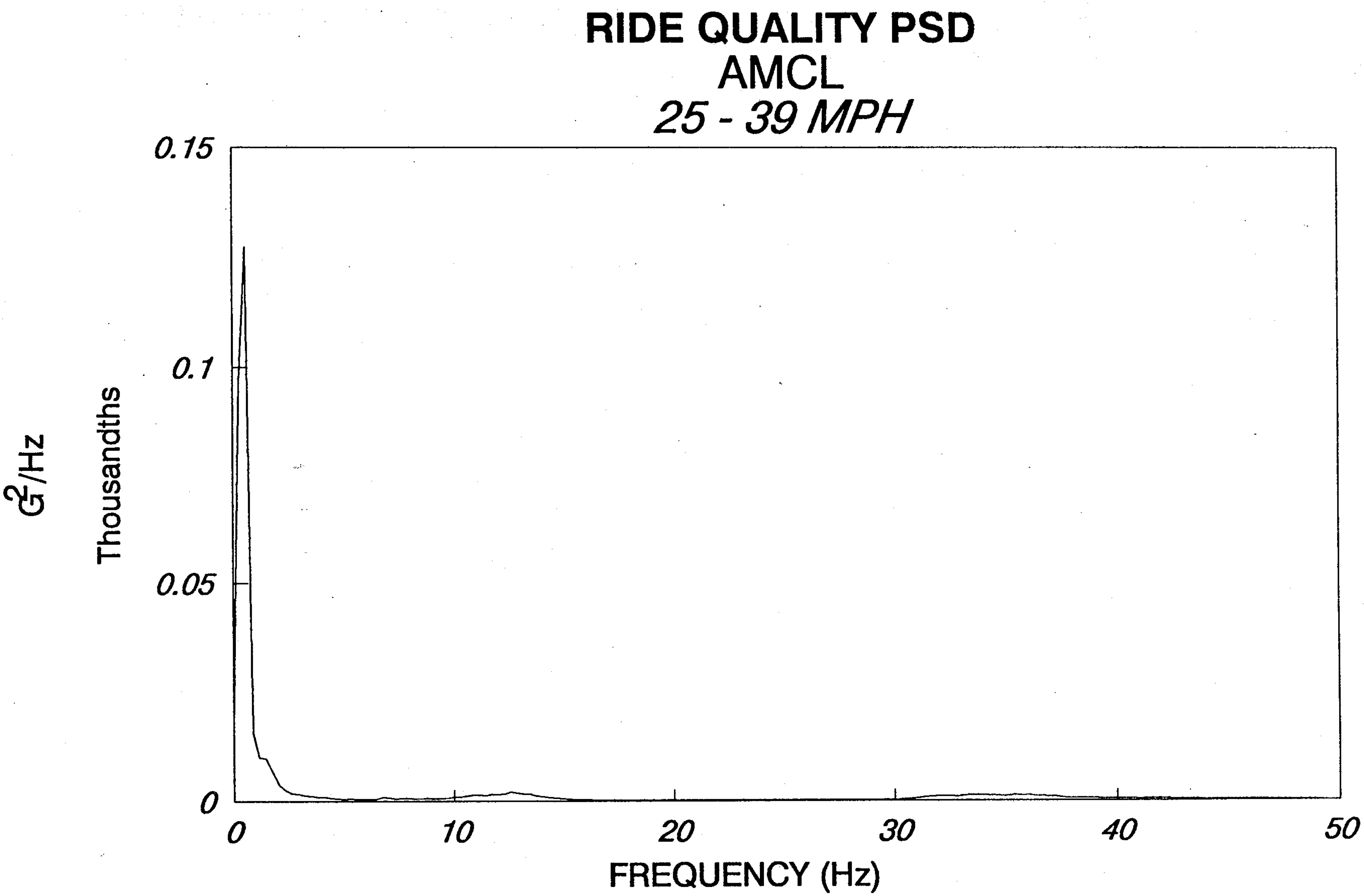
RMS = 0.120 G's
WEIGHT = 525,900 LBS.



RMS = 0.044 G's
WEIGHT = 525,900 LBS.



RMS = 0.021 G's
WEIGHT = 166,000 LBS.

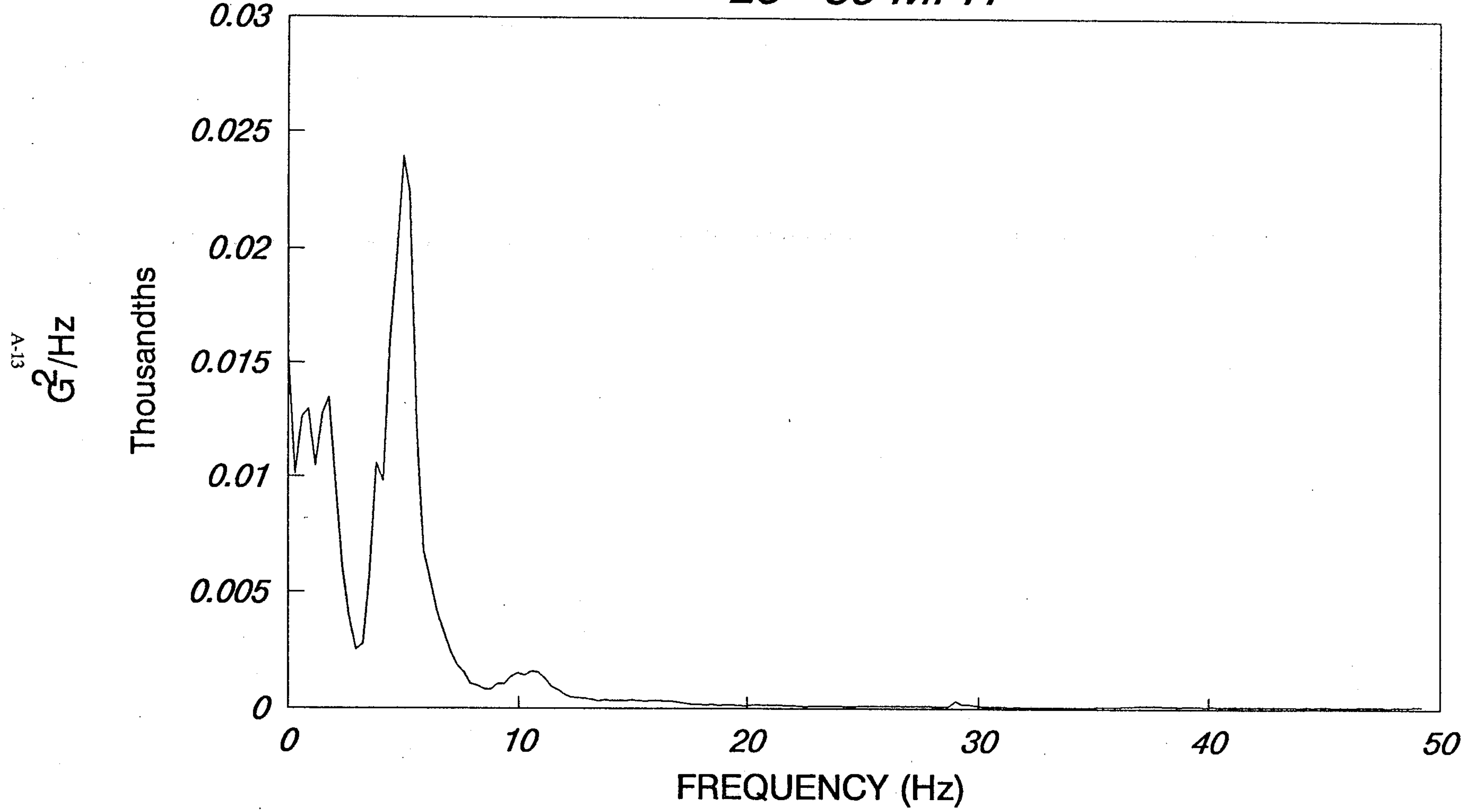


RMS = 0.018 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD

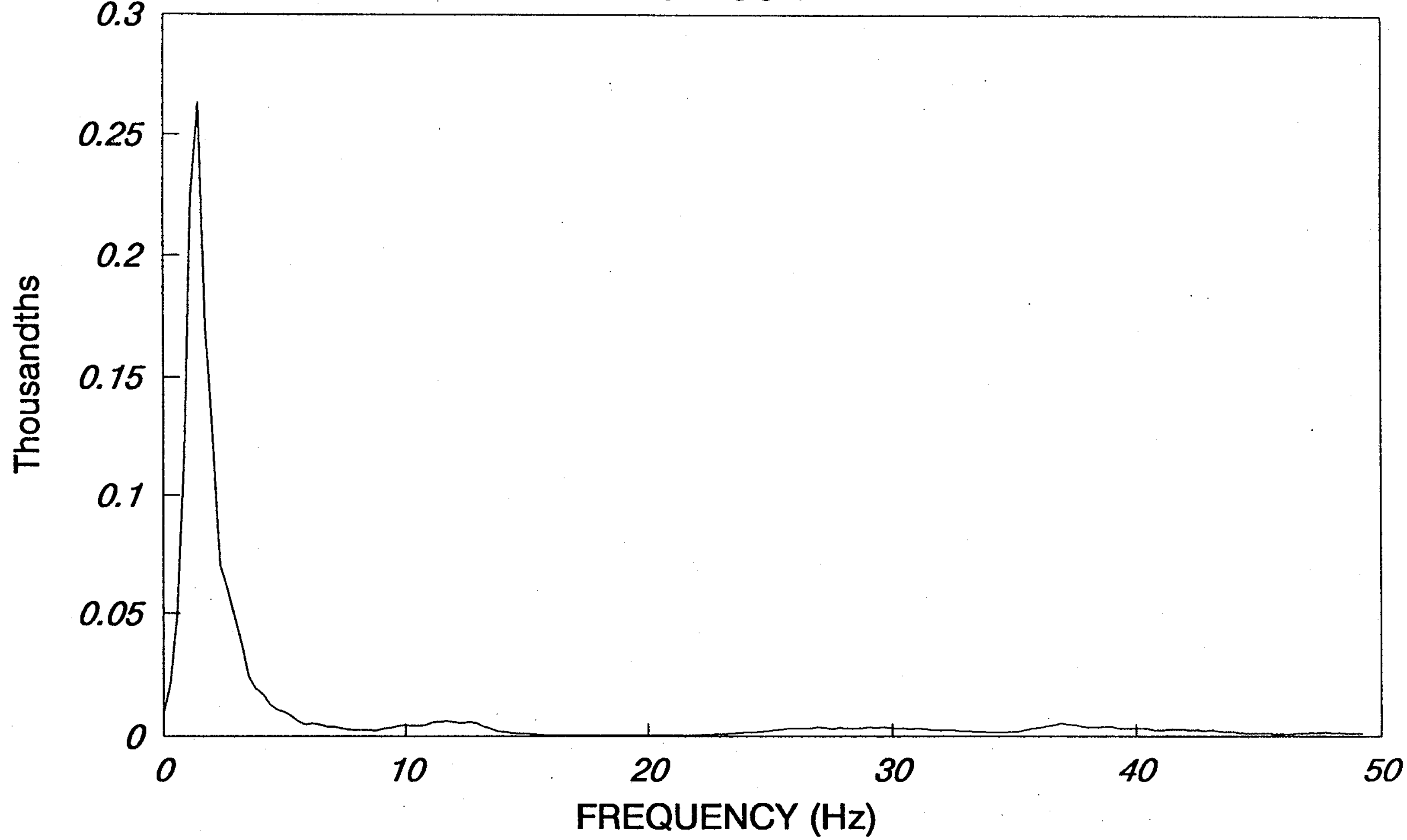
AACV

25 - 39 MPH



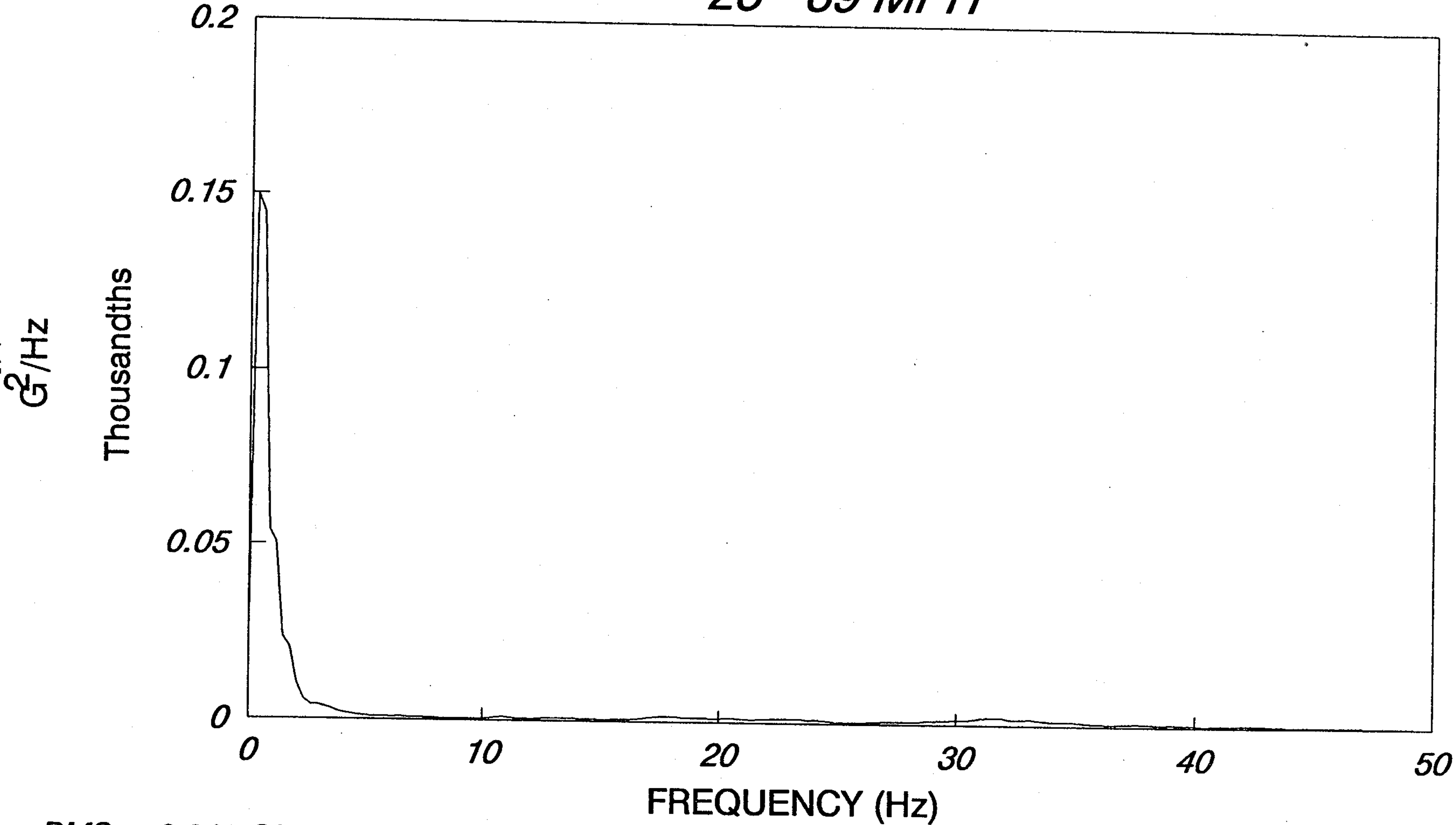
RMS = 0.015 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD
AACL
25 - 39 MPH

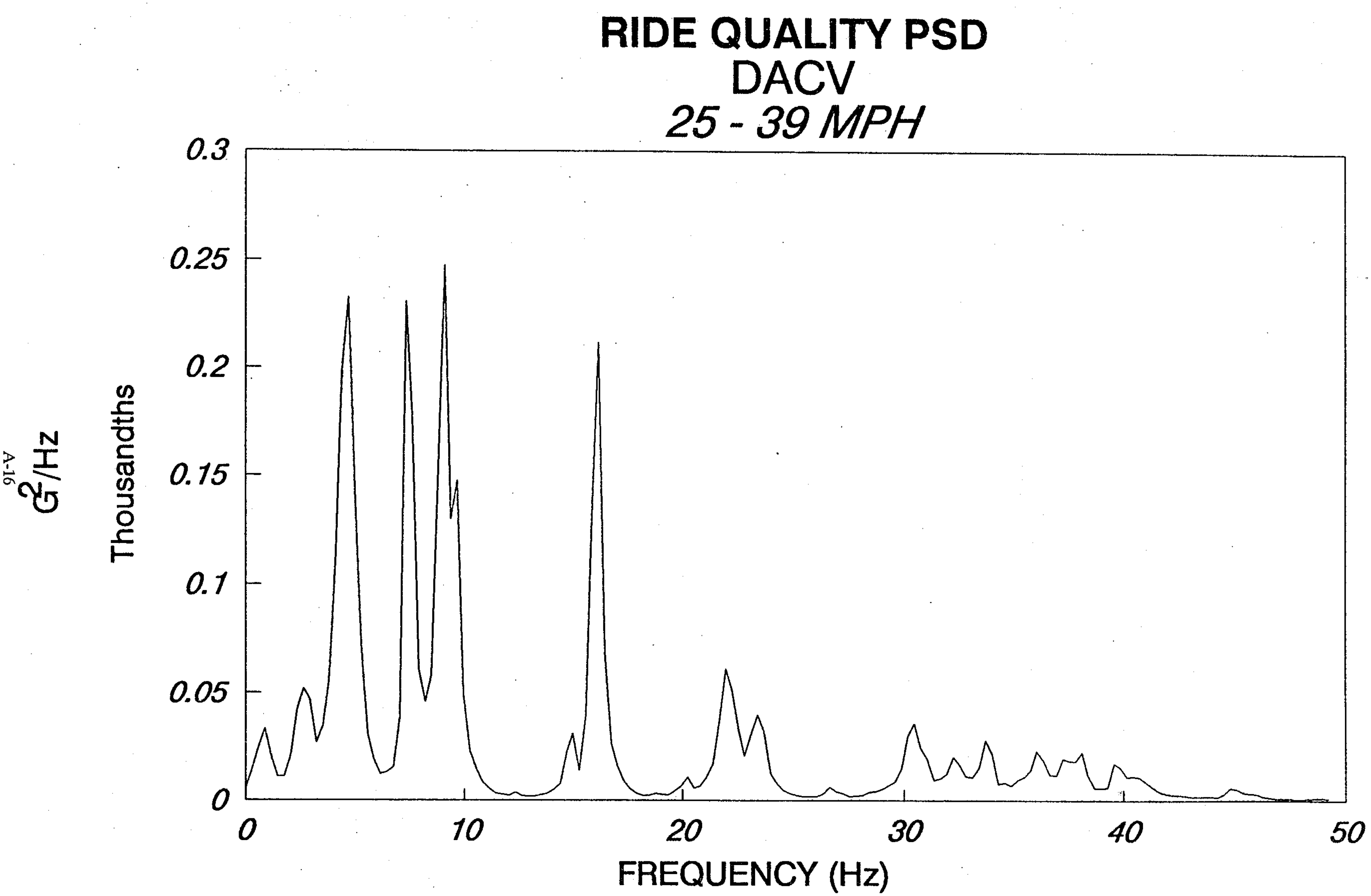


RMS = 0.026 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD
AACN
25 - 39 MPH

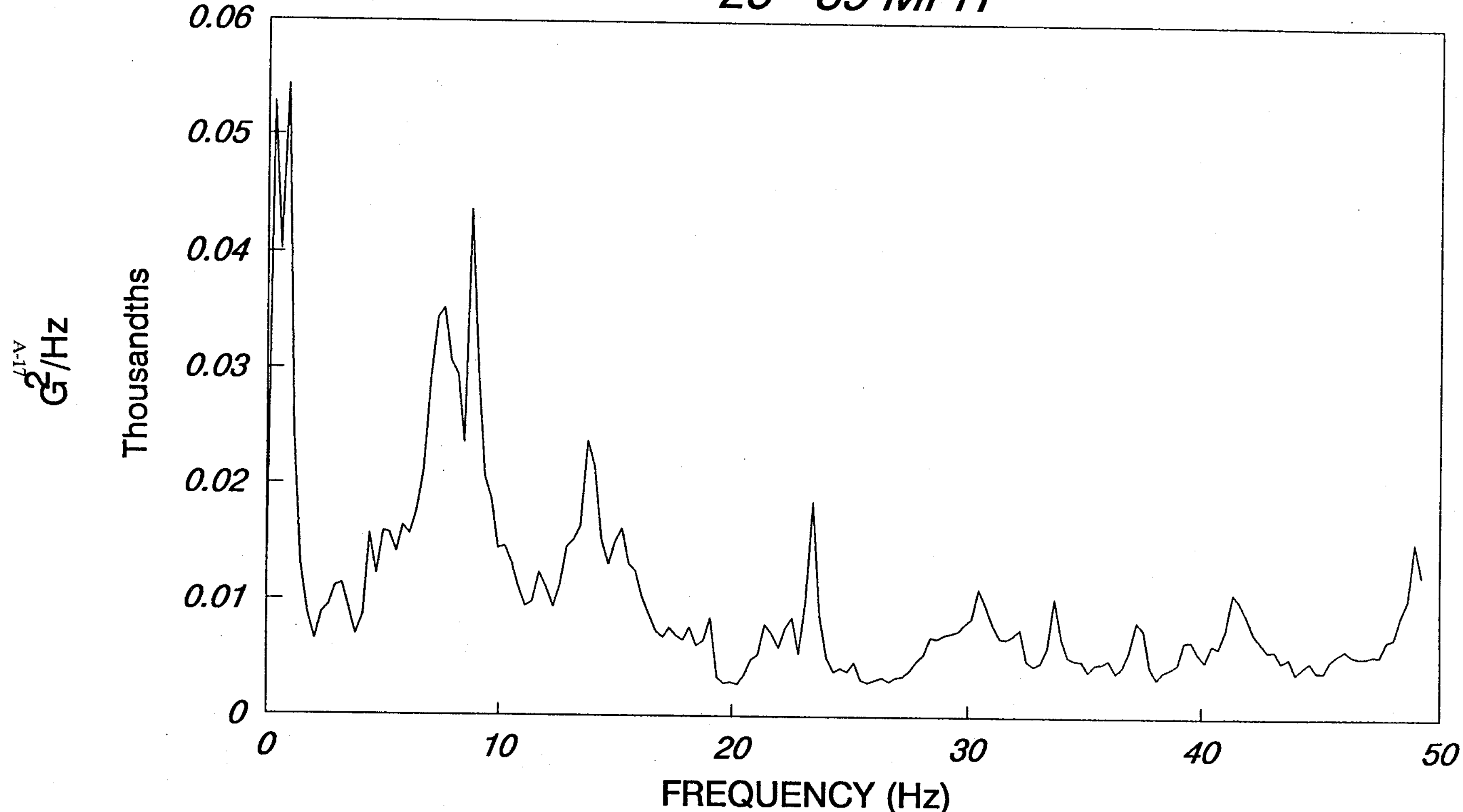


RMS = 0.019 G's
WEIGHT = 166,000 LBS.

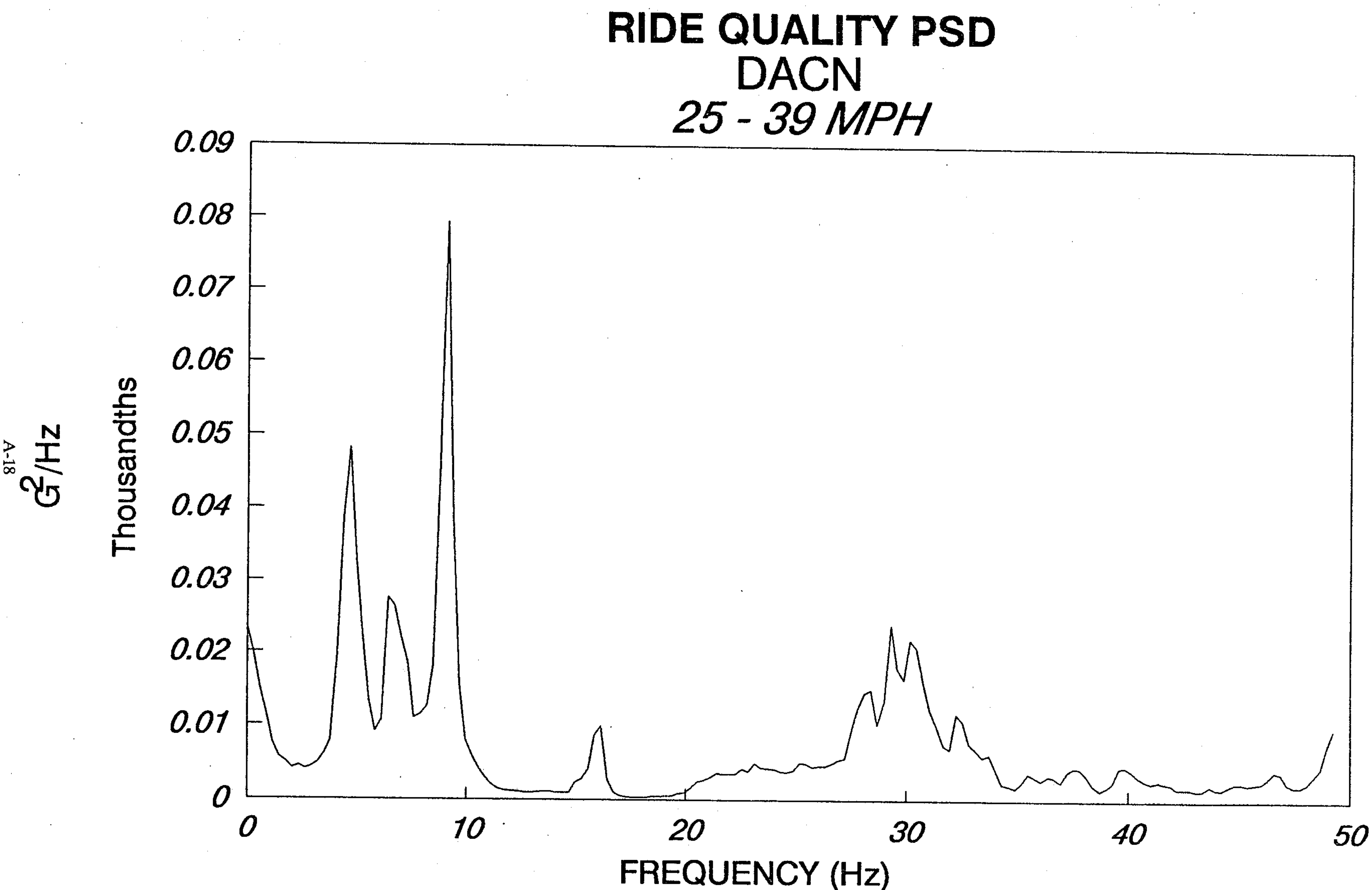


RMS = 0.038 G's
WEIGHT = 525,900 LBS.

RIDE QUALITY PSD
DACL
25 - 39 MPH

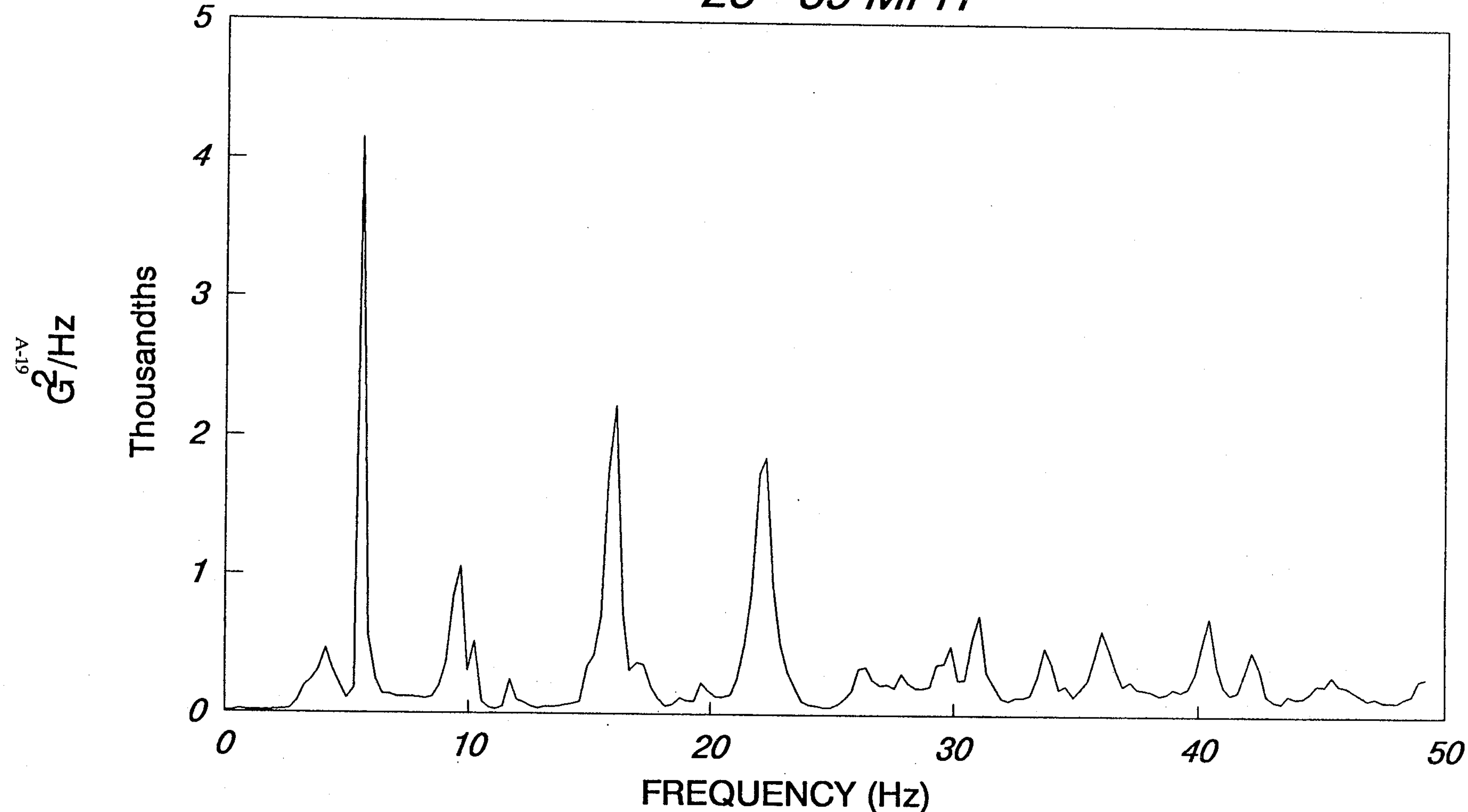


RMS = 0.030 G's
WEIGHT = 525,900 LBS.

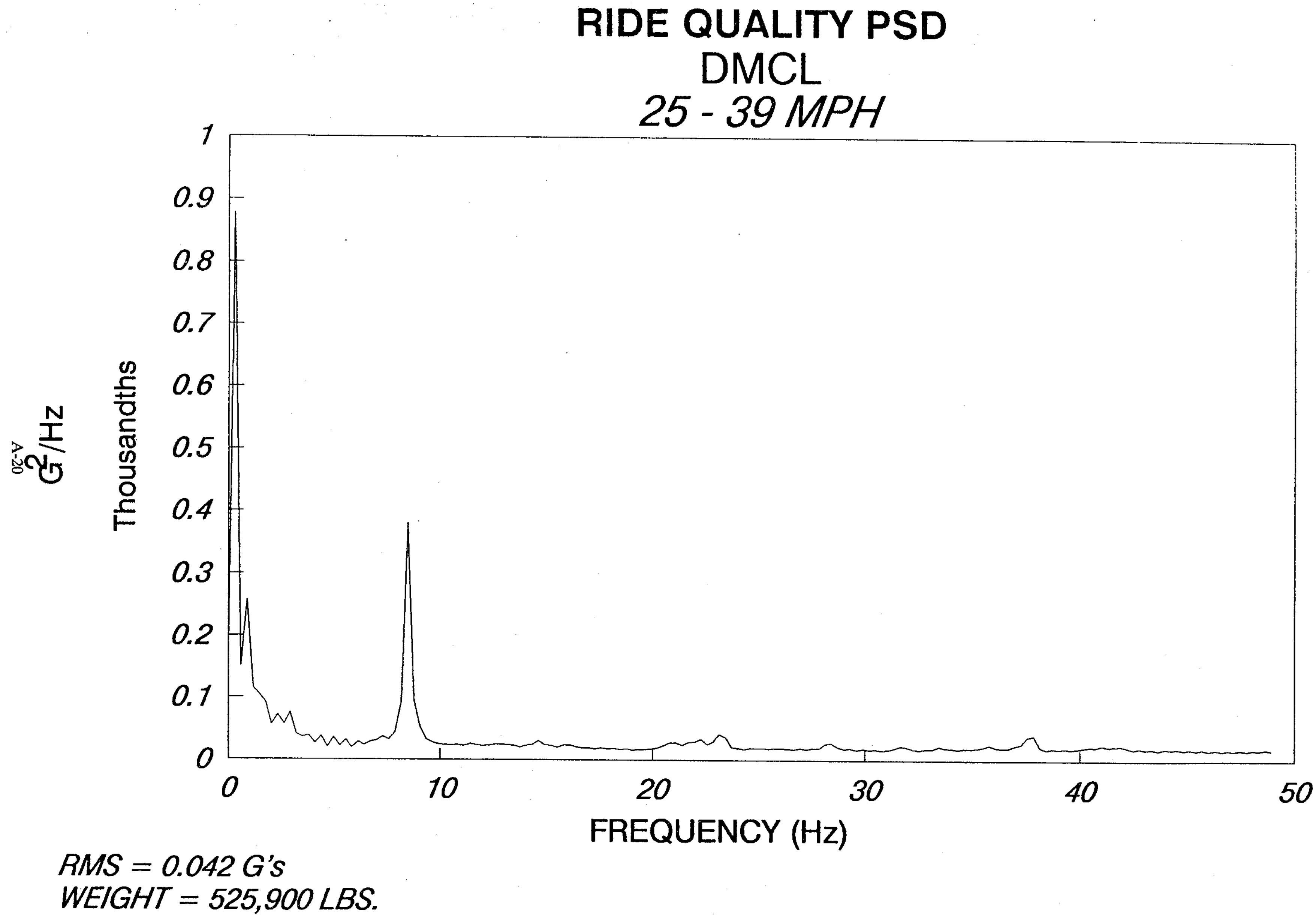


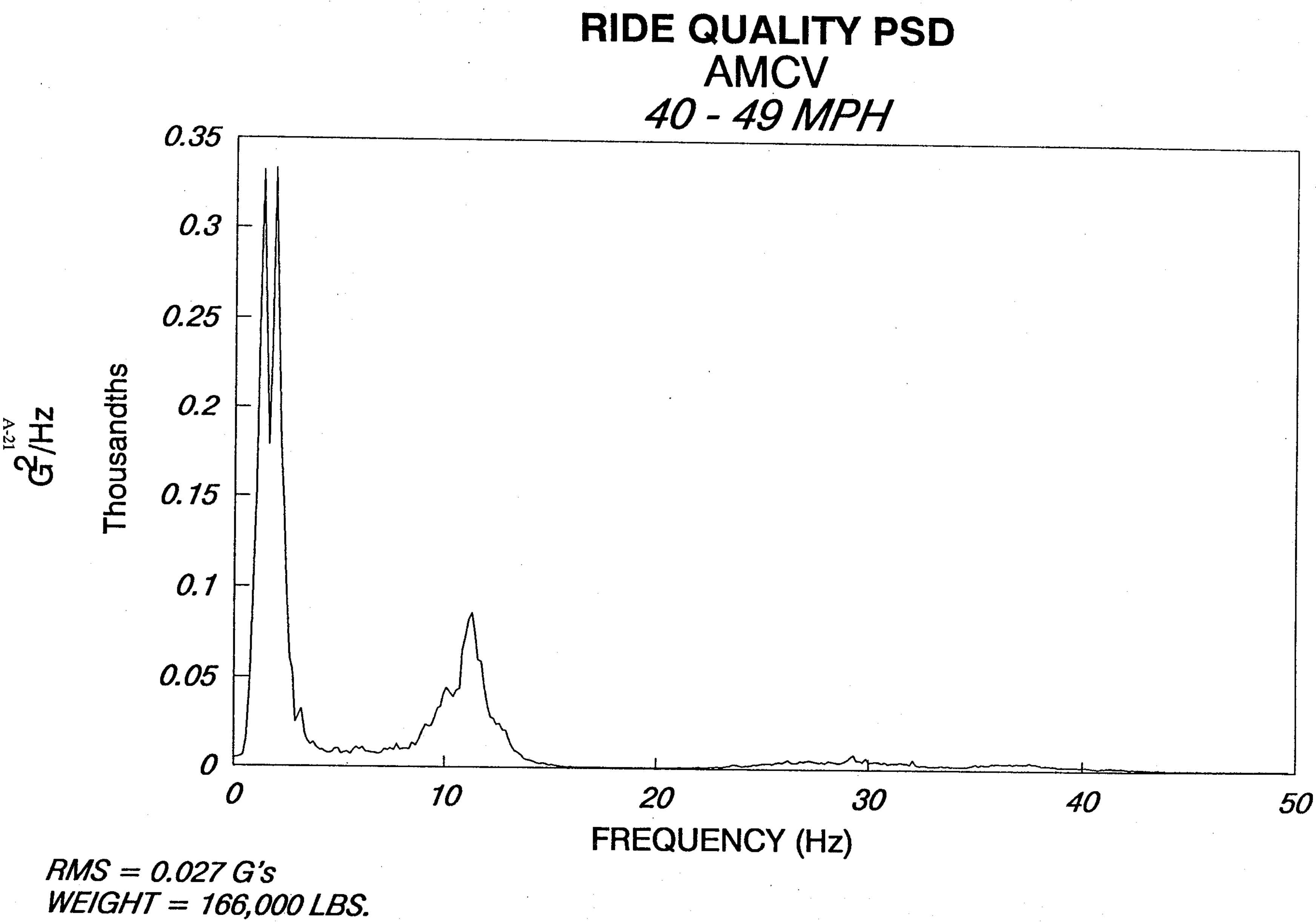
RMS = 0.026 G's
WEIGHT = 525,900 LBS.

RIDE QUALITY PSD
DMCV
25 - 39 MPH

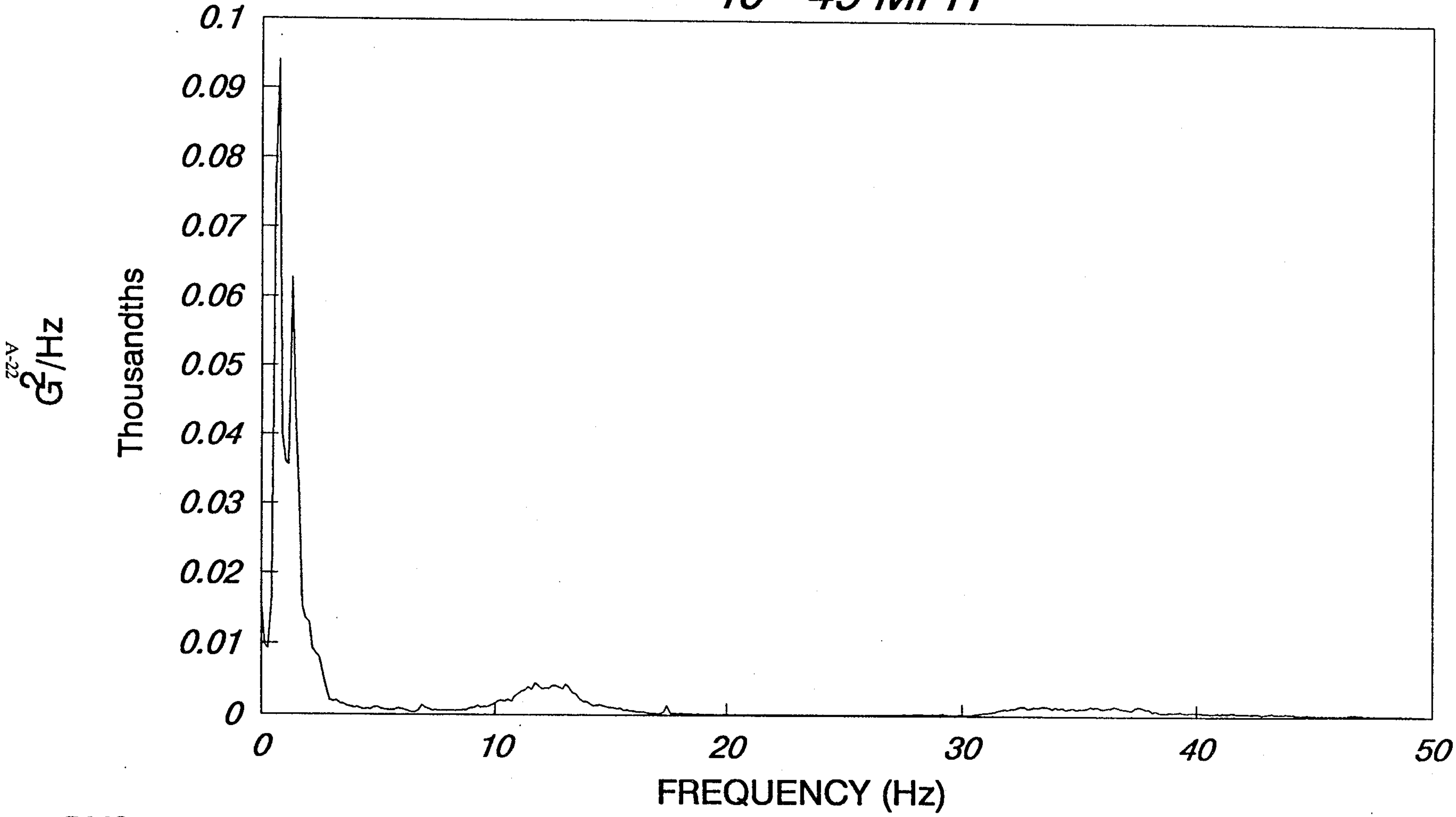


RMS = 0.143 G's
WEIGHT = 525,900 LBS.

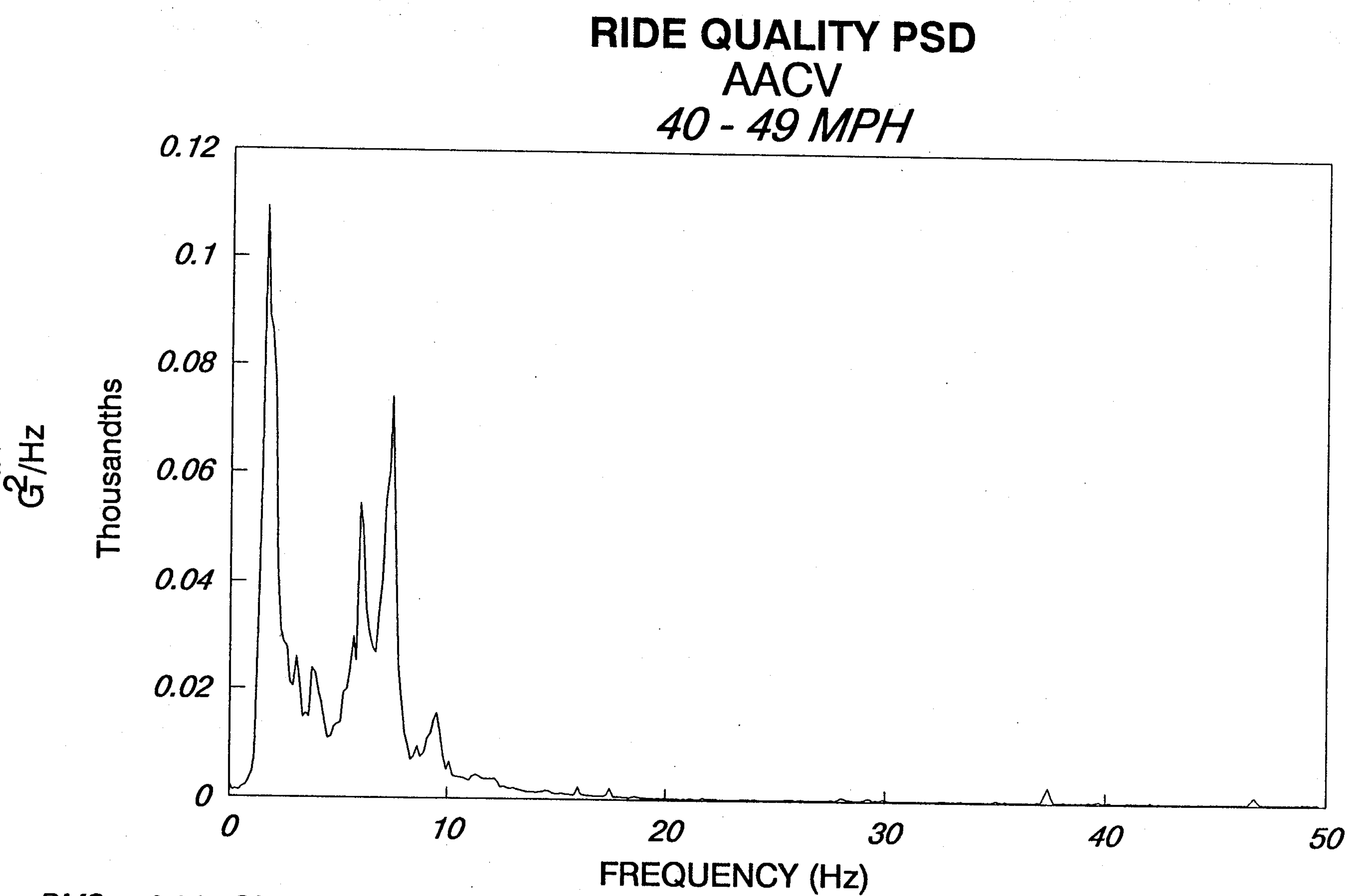

RIDE QUALITY PSD
DMCL
25 - 39 MPH
G²/Hz
Thousandths
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.042 G's
WEIGHT = 525,900 LBS.


RIDE QUALITY PSD
AMCV
40 - 49 MPH
G²/Hz
Thousandths
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.027 G's
WEIGHT = 166,000 LBS.

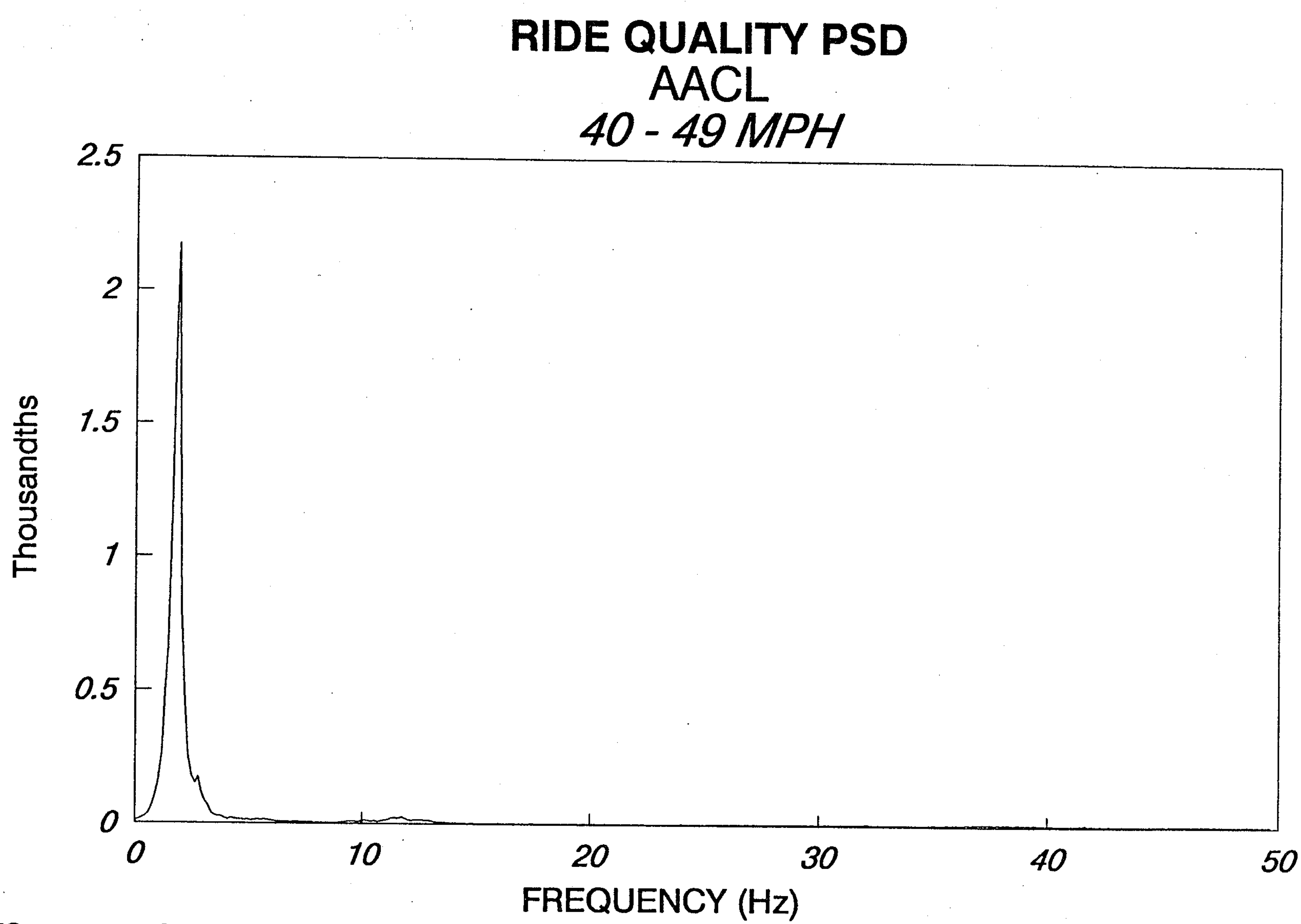
RIDE QUALITY PSD
AMCL
40 - 49 MPH



RMS = 0.011 G's
WEIGHT = 166,000 LBS.

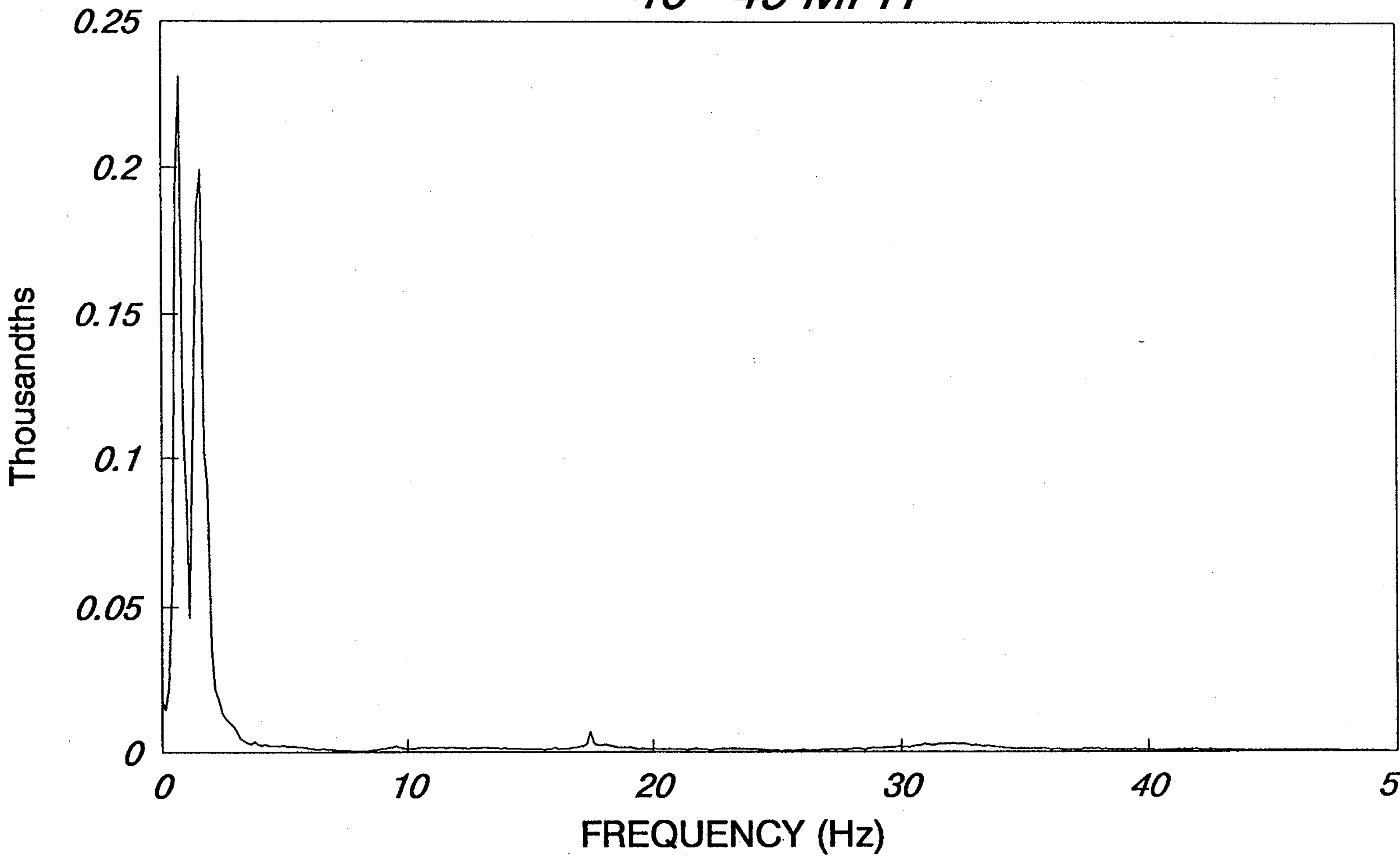


RMS = 0.017 G's
WEIGHT = 166,000 LBS.

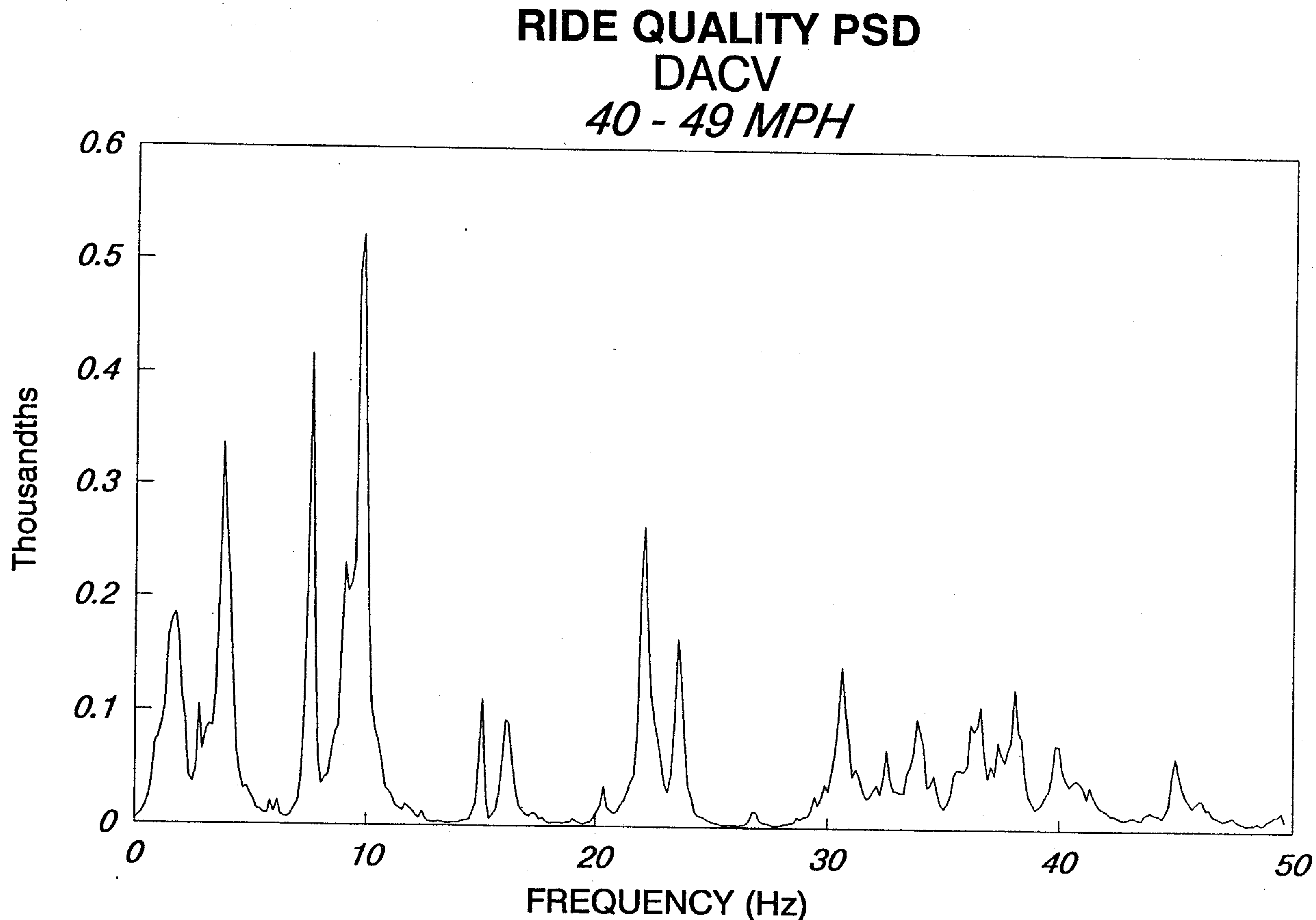


RMS = 0.040 G's
WEIGHT = 166,000 LBS.

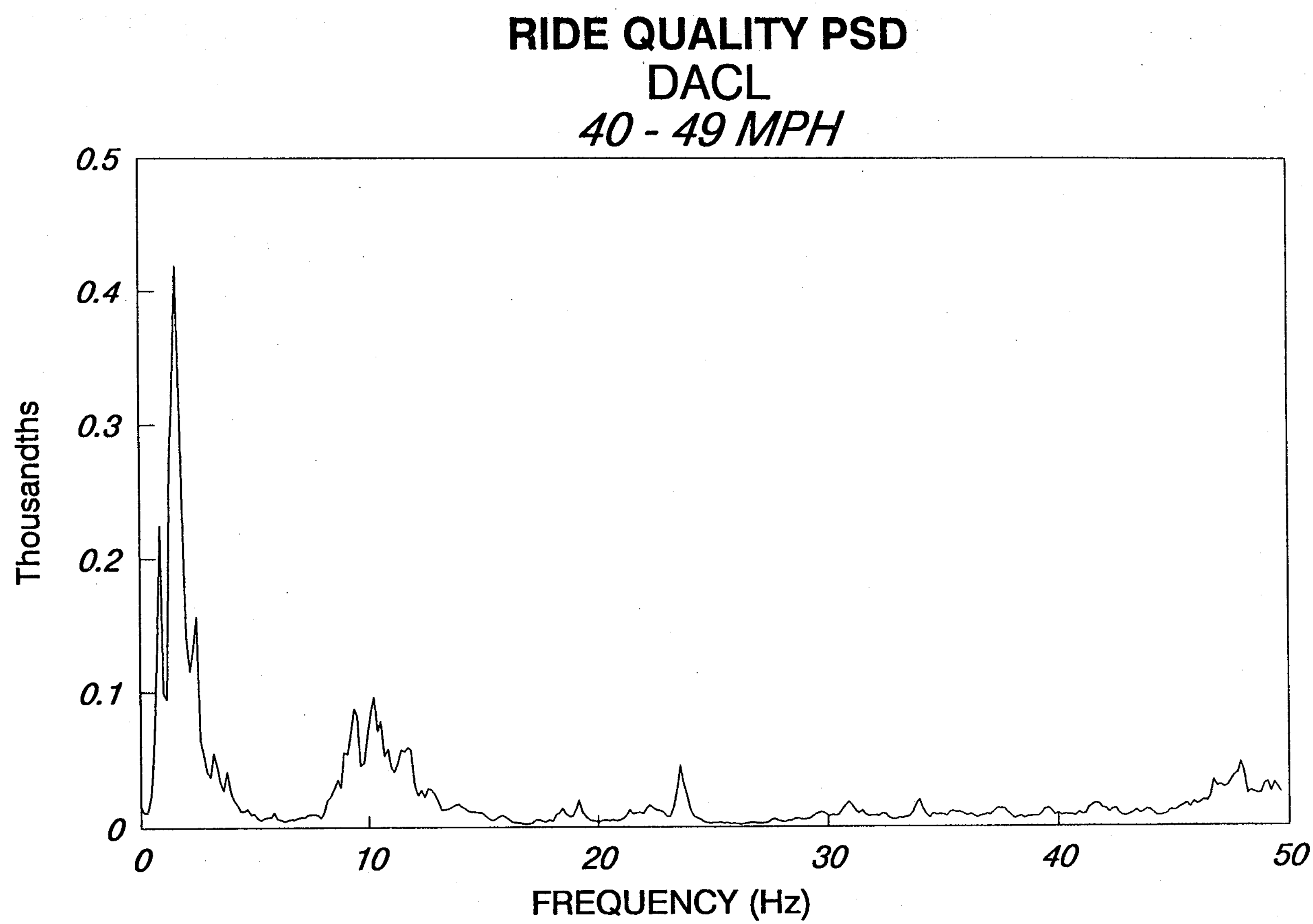
RIDE QUALITY PSD
AACN
40 - 49 MPH



RMS = 0.017 G's
WEIGHT = 166,000 LBS.

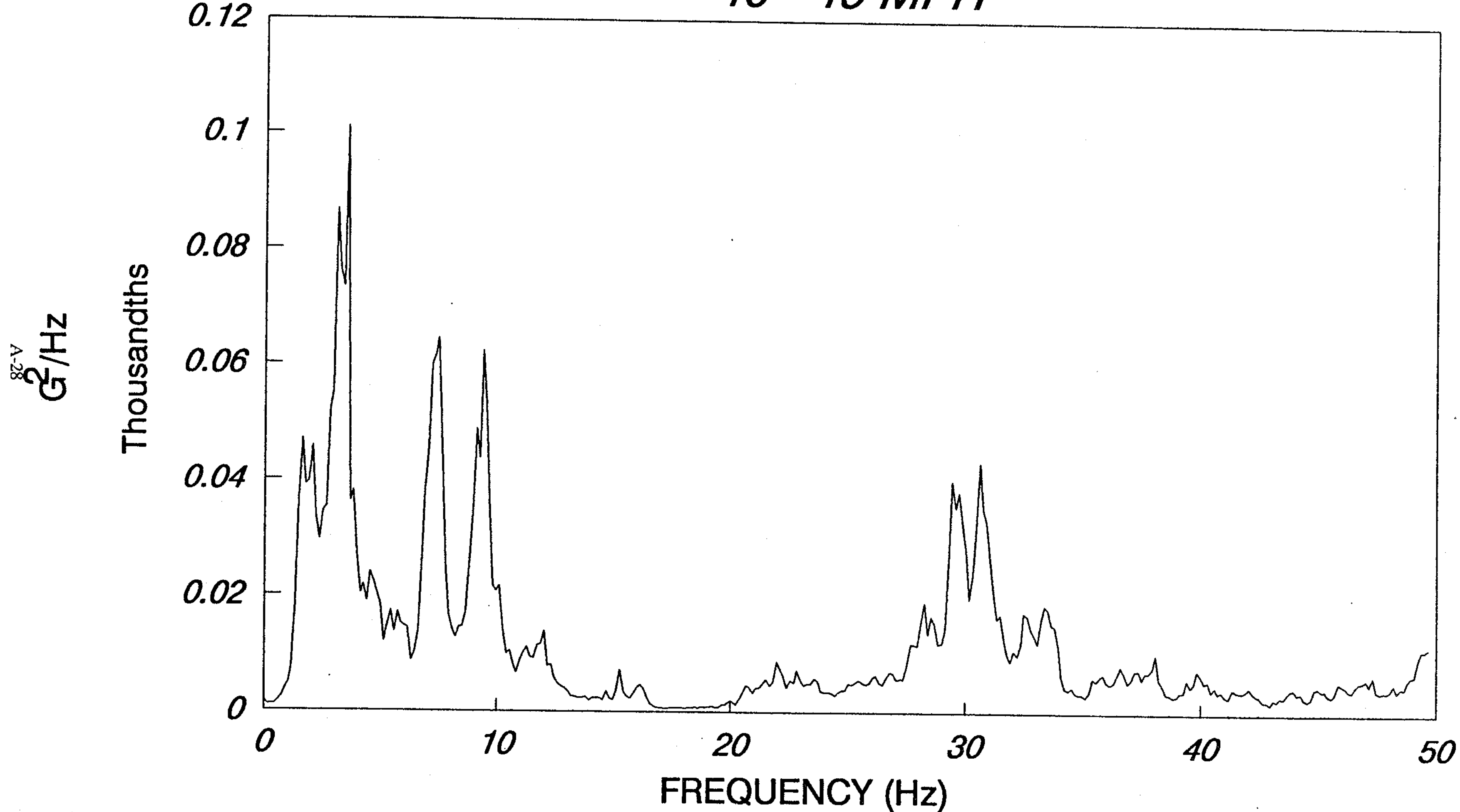


RMS = 0.052 G's
WEIGHT = 525,900 LBS.

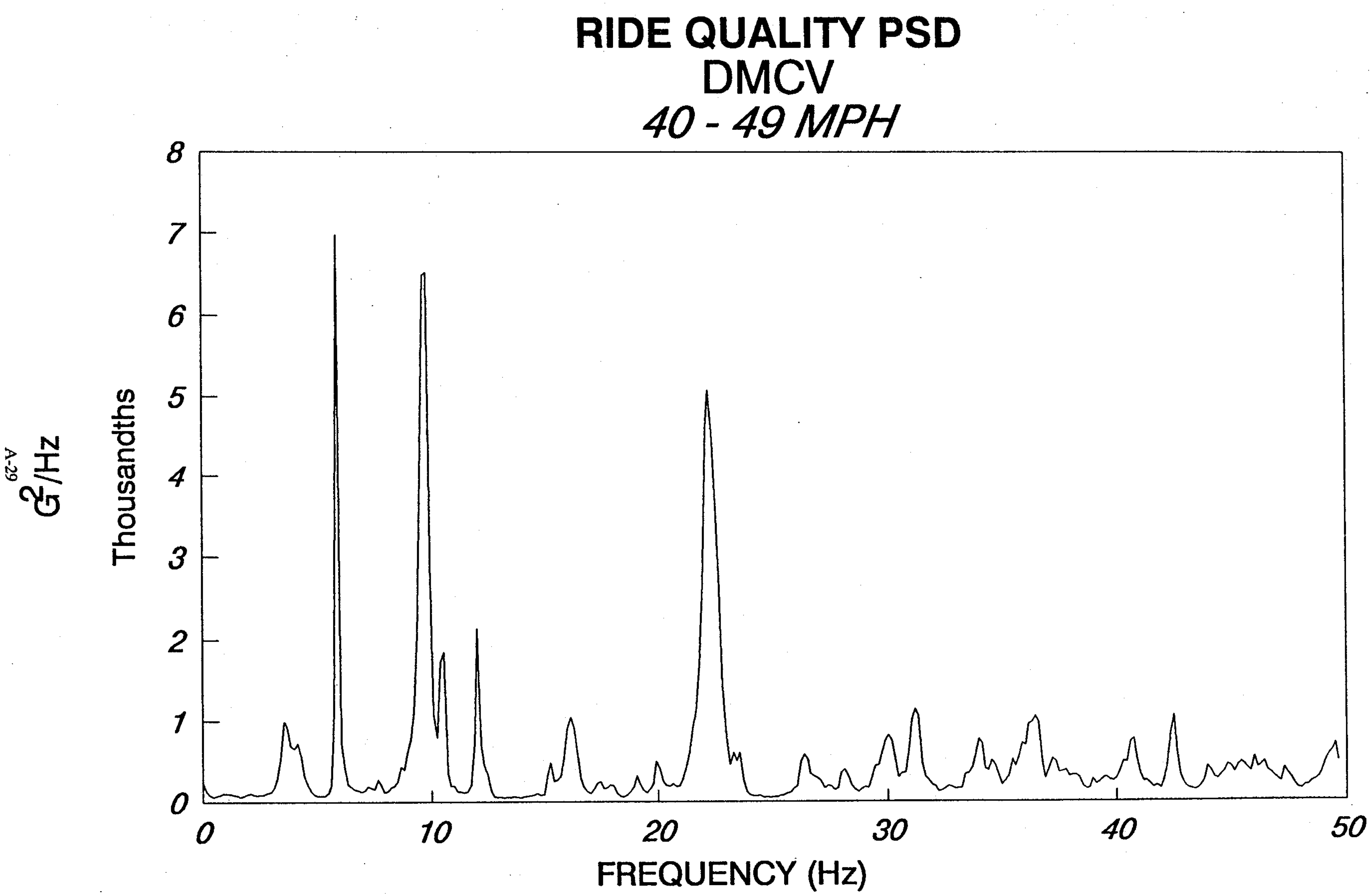


RMS = 0.038 G's
WEIGHT = 525,900 LBS.

RIDE QUALITY PSD
DACN
40 - 49 MPH

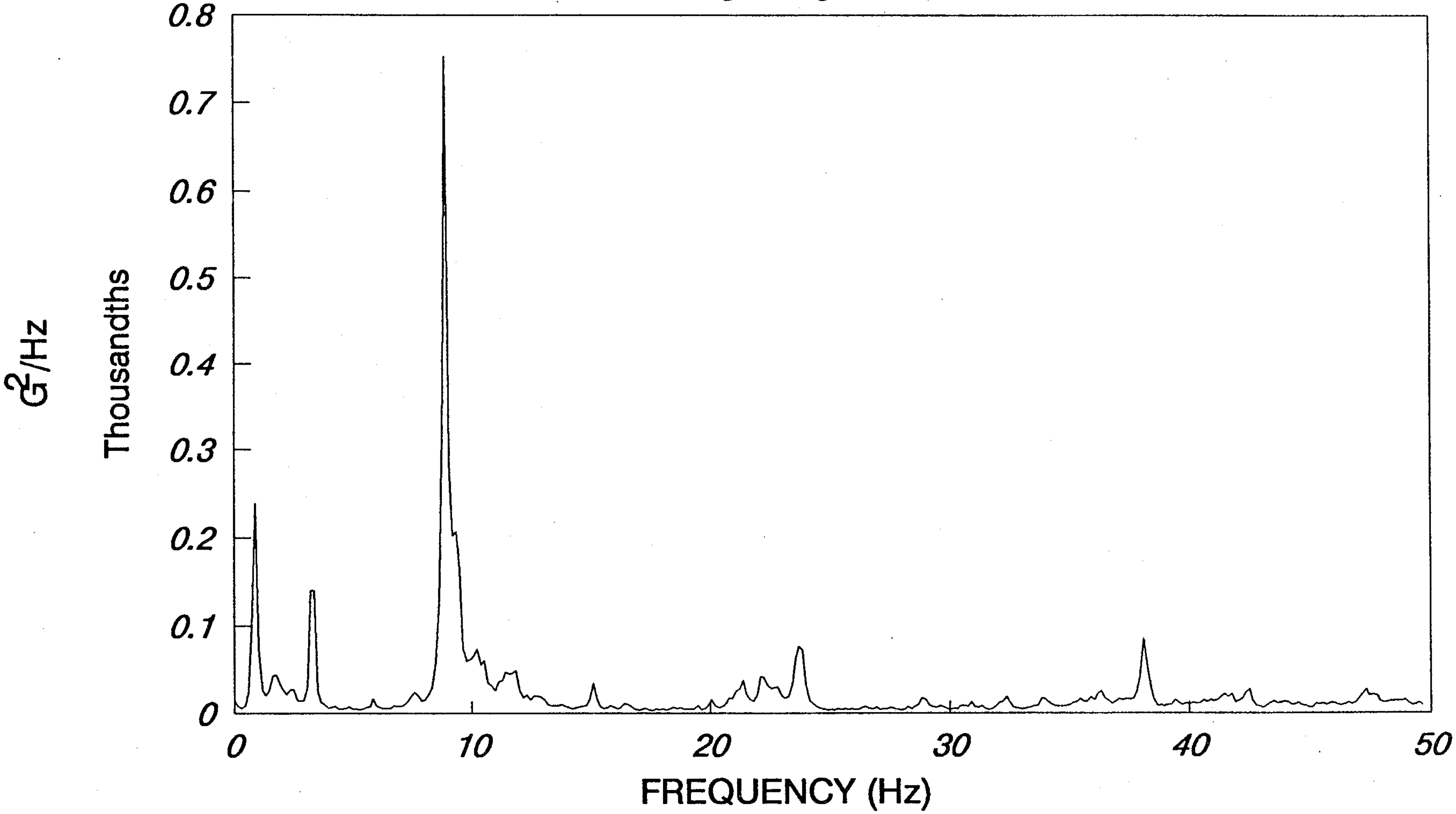


RMS = 0.027 G's
WEIGHT = 525,900 LBS.



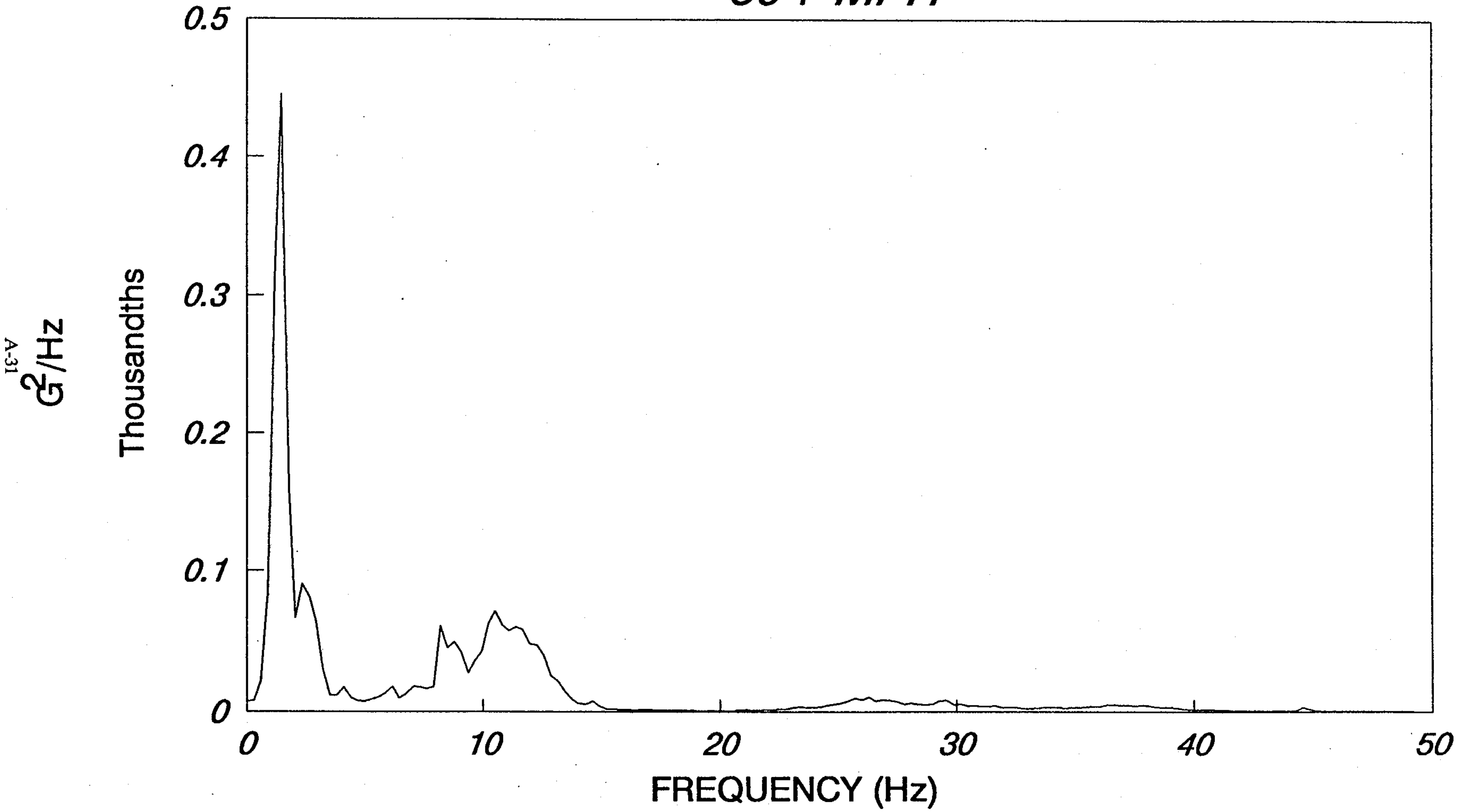
RMS = 0.187 G's
WEIGHT = 525,900 LBS.

RIDE QUALITY PSD
DMCL
40 - 49 MPH



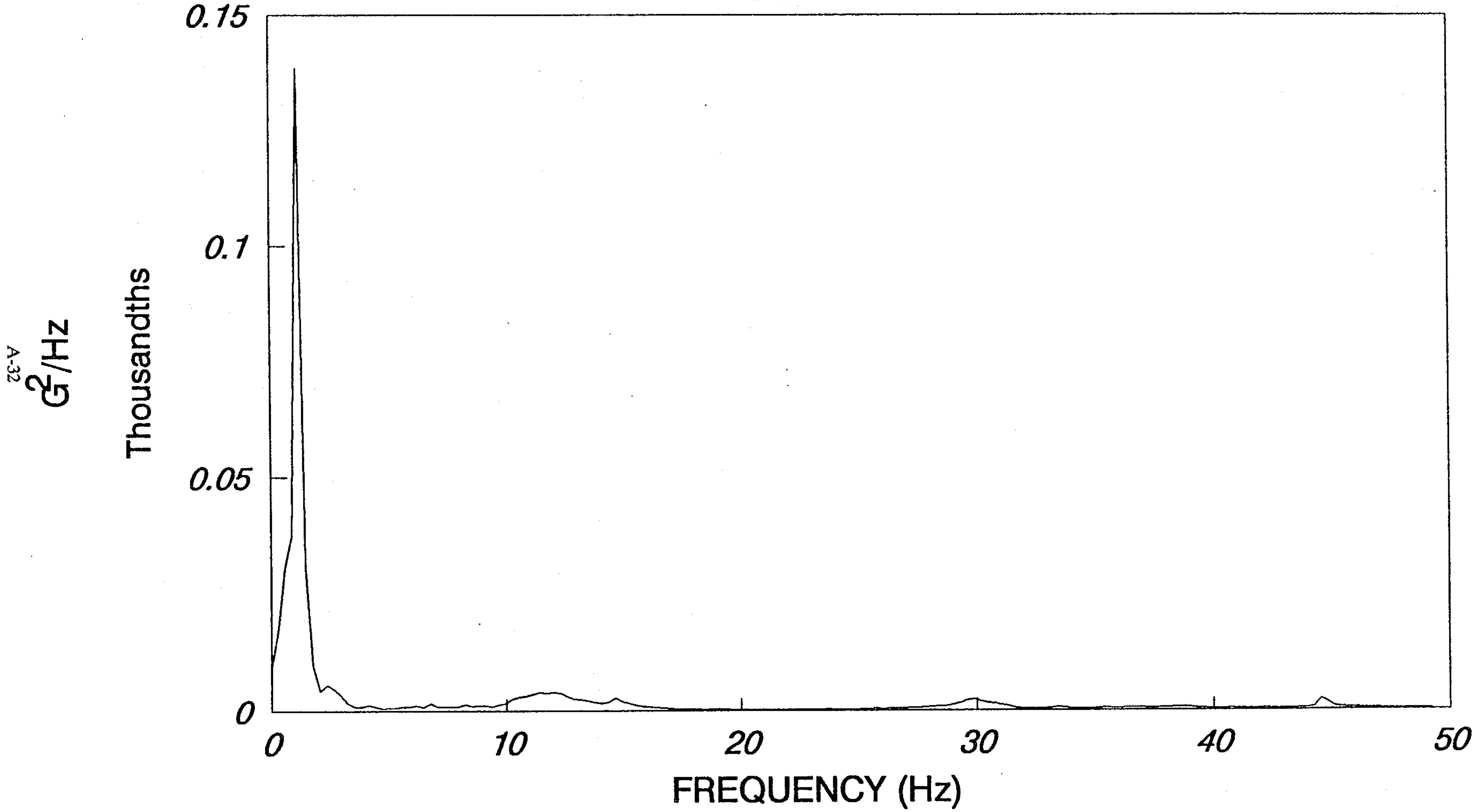
RMS = 0.042 G's
WEIGHT = 525,900 LBS.

RIDE QUALITY PSD
AMCV
50+ MPH

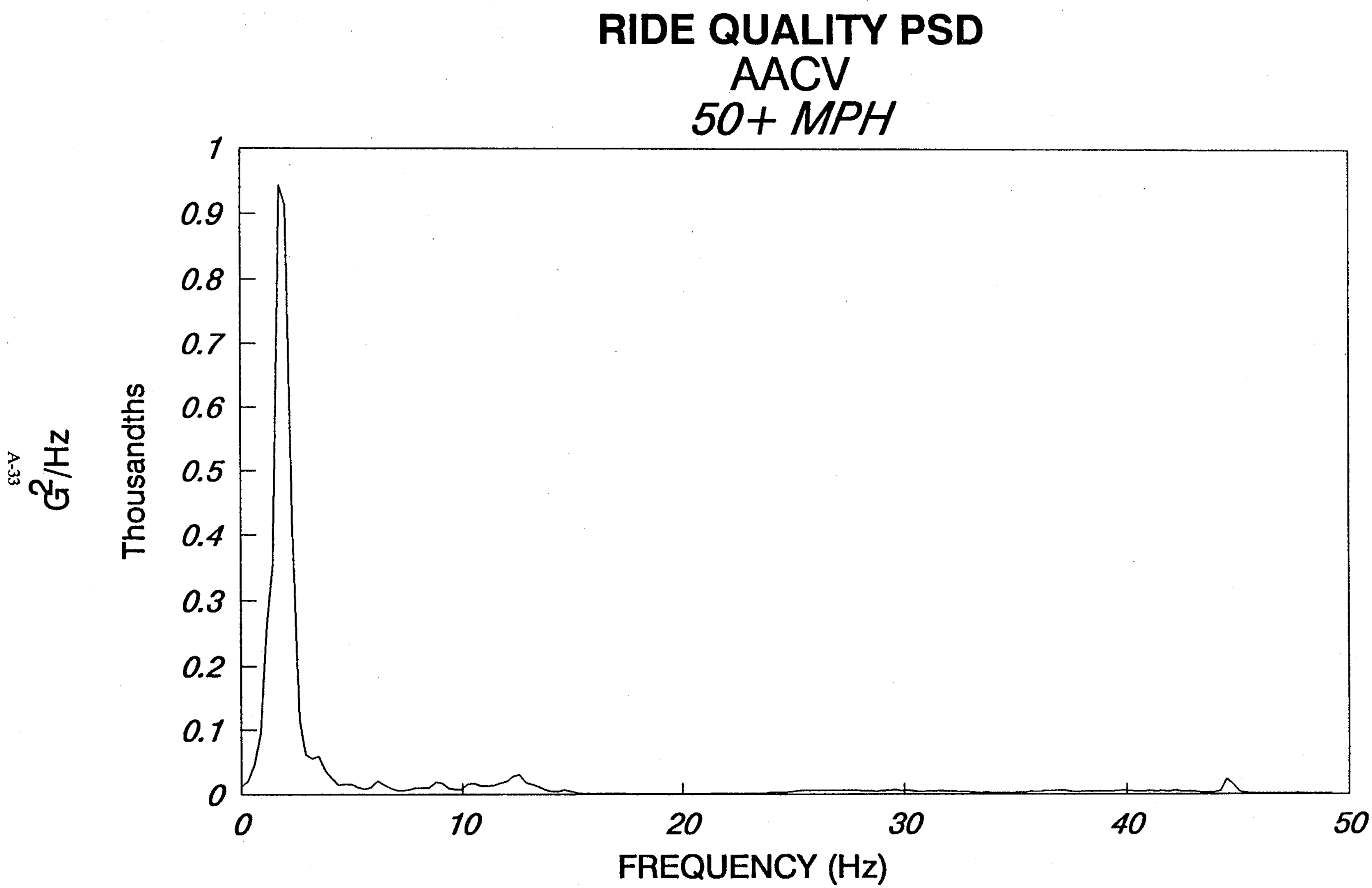


RMS = 0.030 G's
WEIGHT = 166,000 LBS.

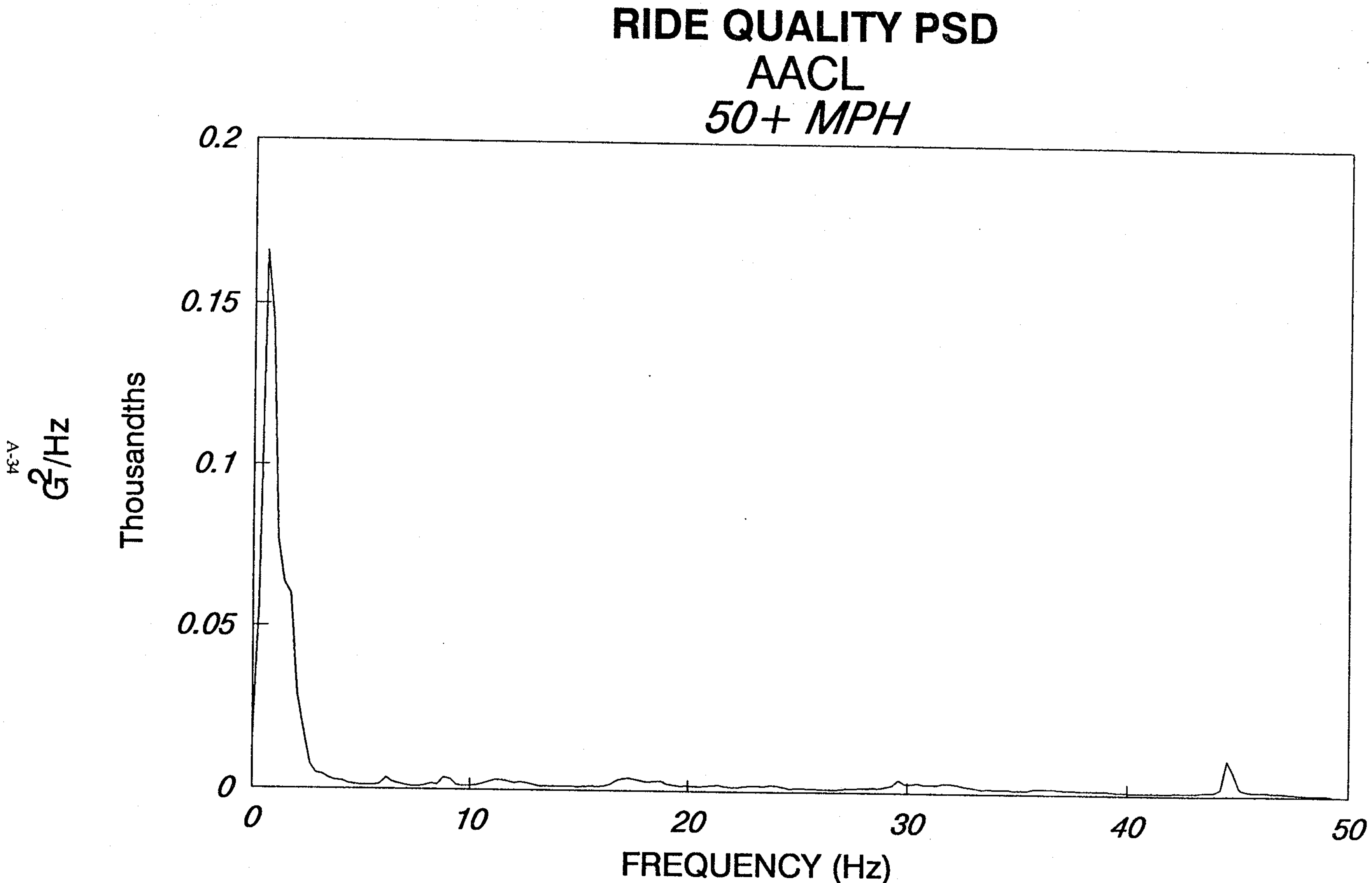
RIDE QUALITY PSD
AMCL
50+ MPH



RMS = 0.018 G's
WEIGHT = 166,000 LBS.

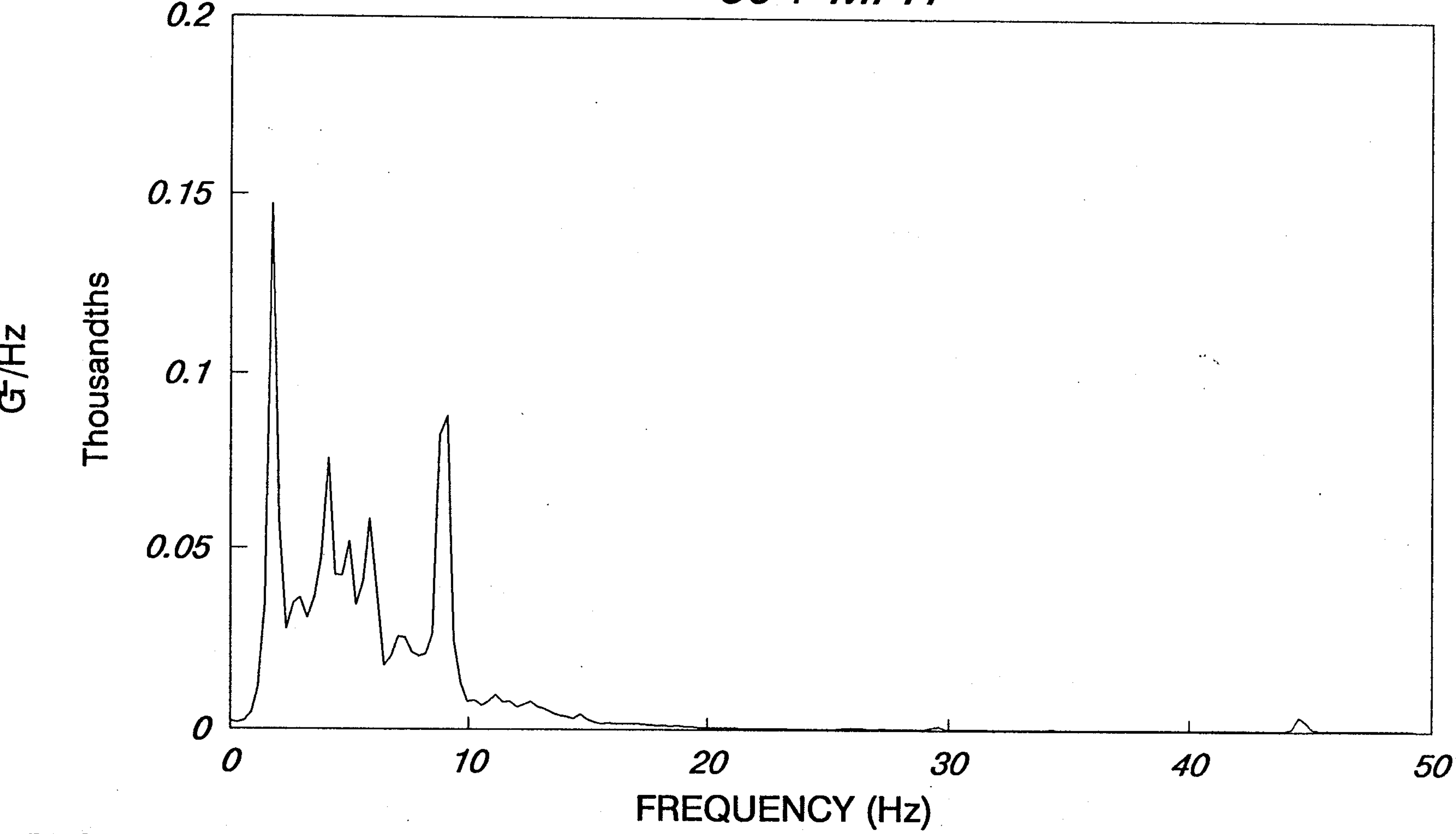


RMS = 0.037 G's
WEIGHT = 166,000 LBS.

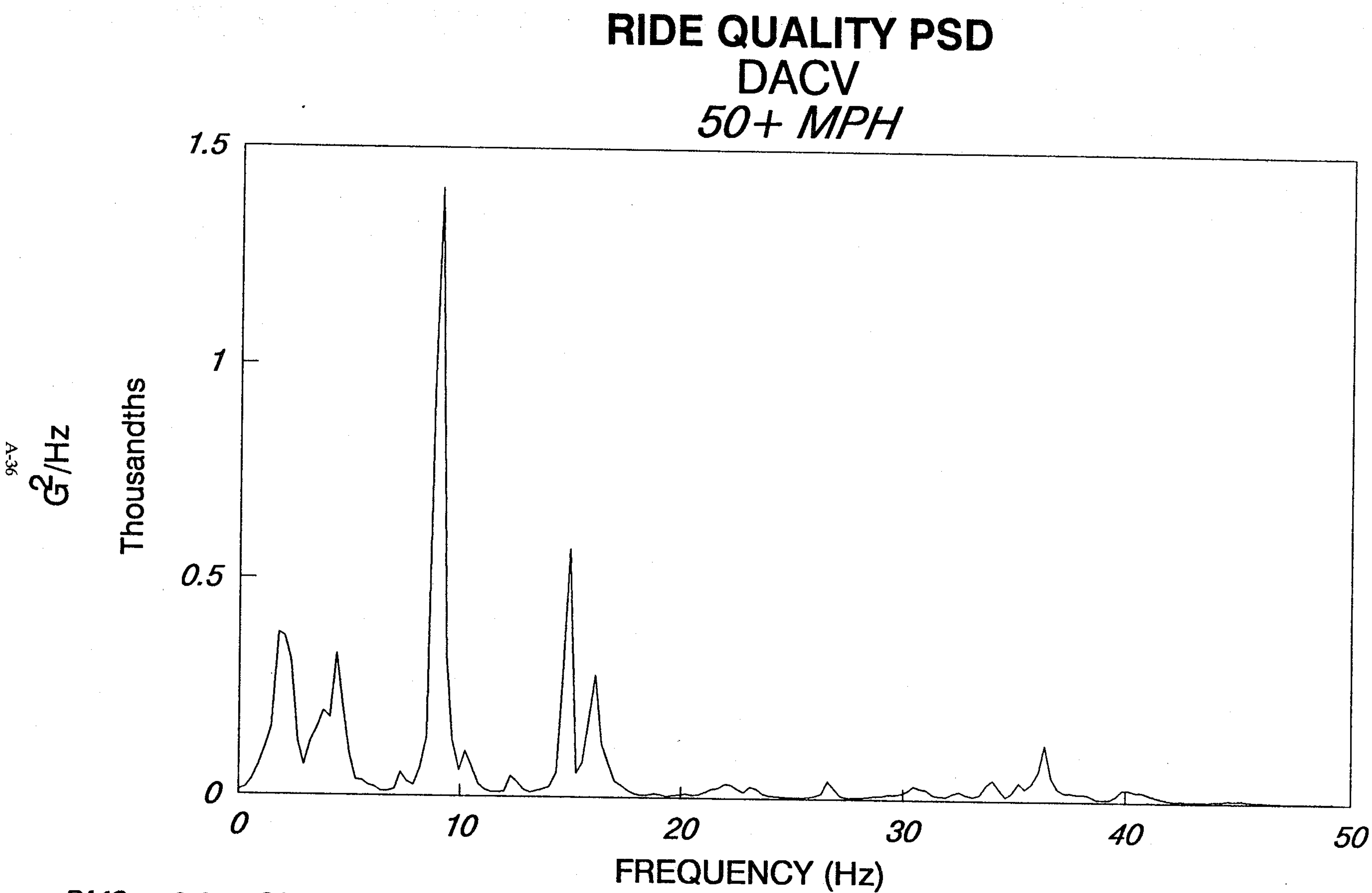


RMS = 0.024 G's
WEIGHT = 166,000 LBS.

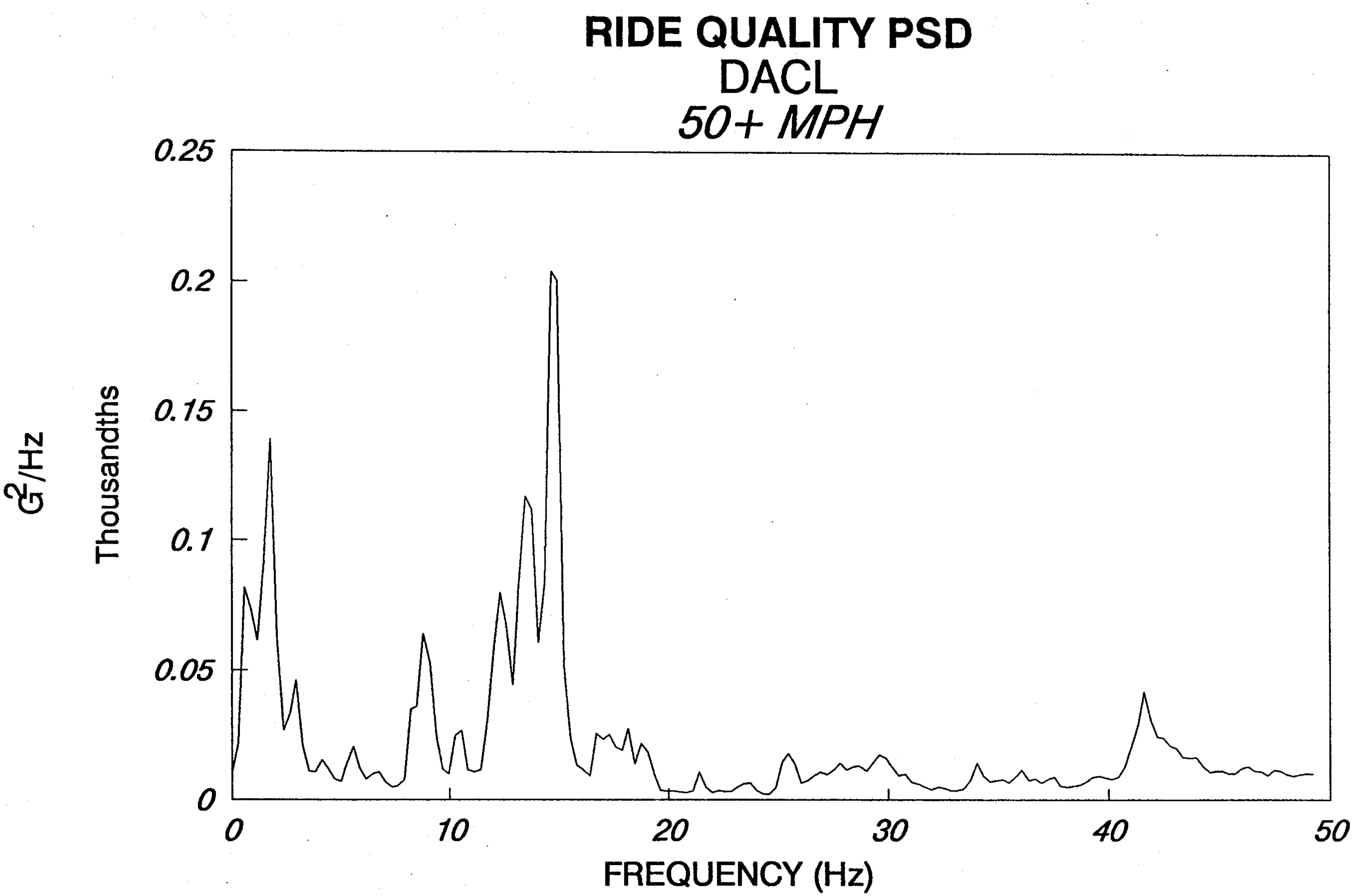
RIDE QUALITY PSD
AACN
50+ MPH



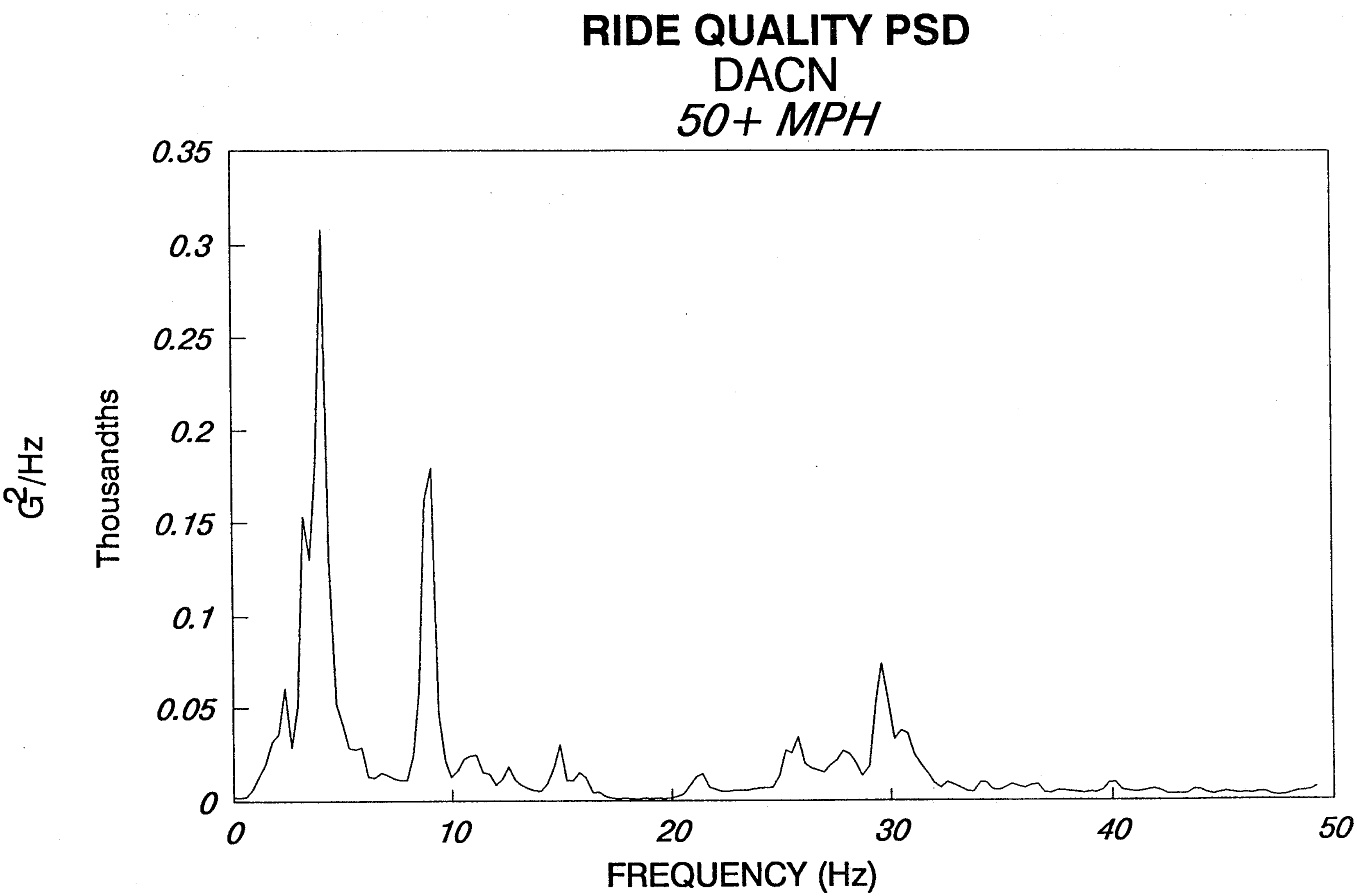
RMS = 0.025 G's
WEIGHT = 166,000 LBS.



RMS = 0.055 G's
WEIGHT = 525,900 LBS.

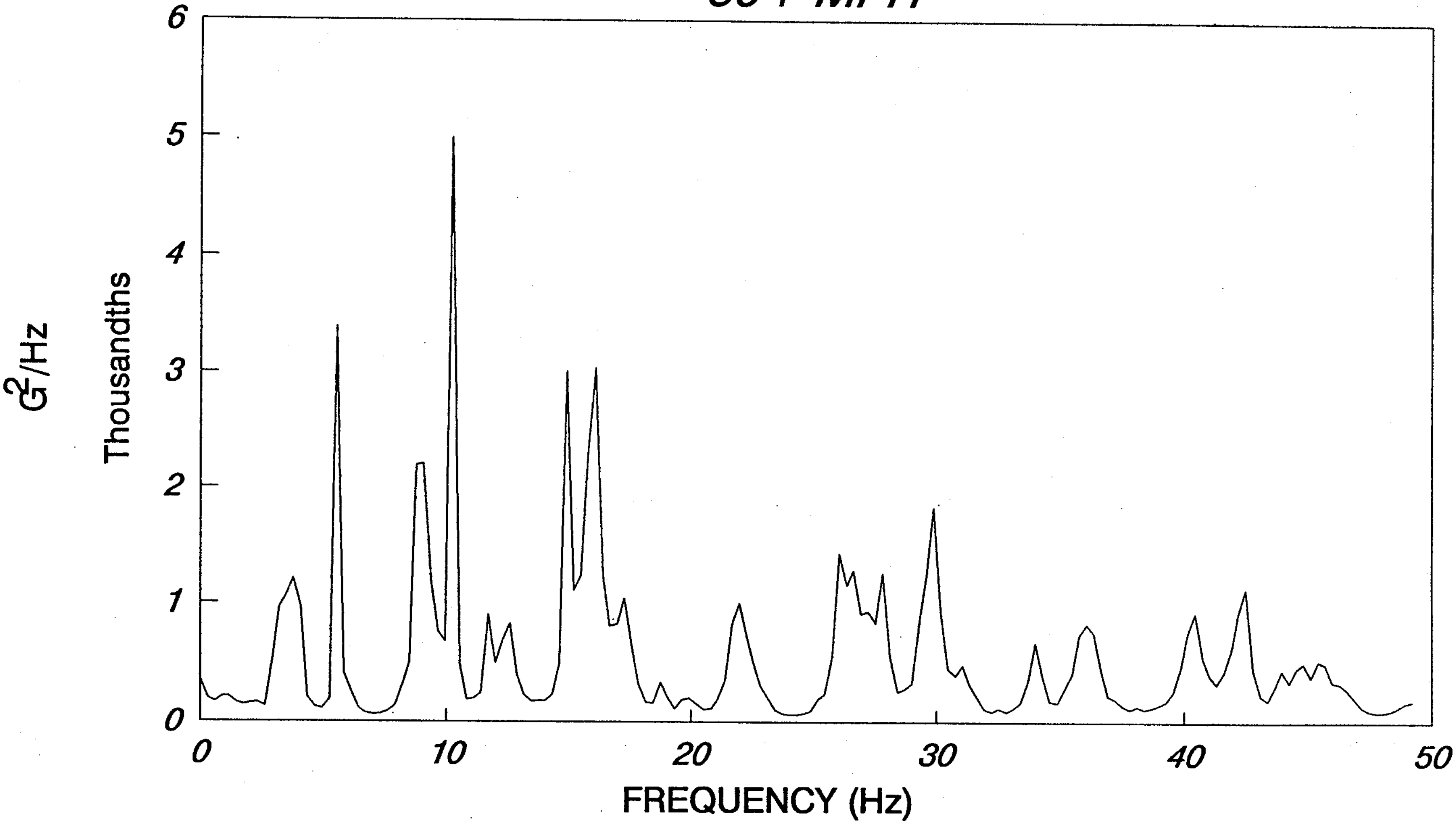


RMS = 0.040 G's
WEIGHT = 525,900 LBS.

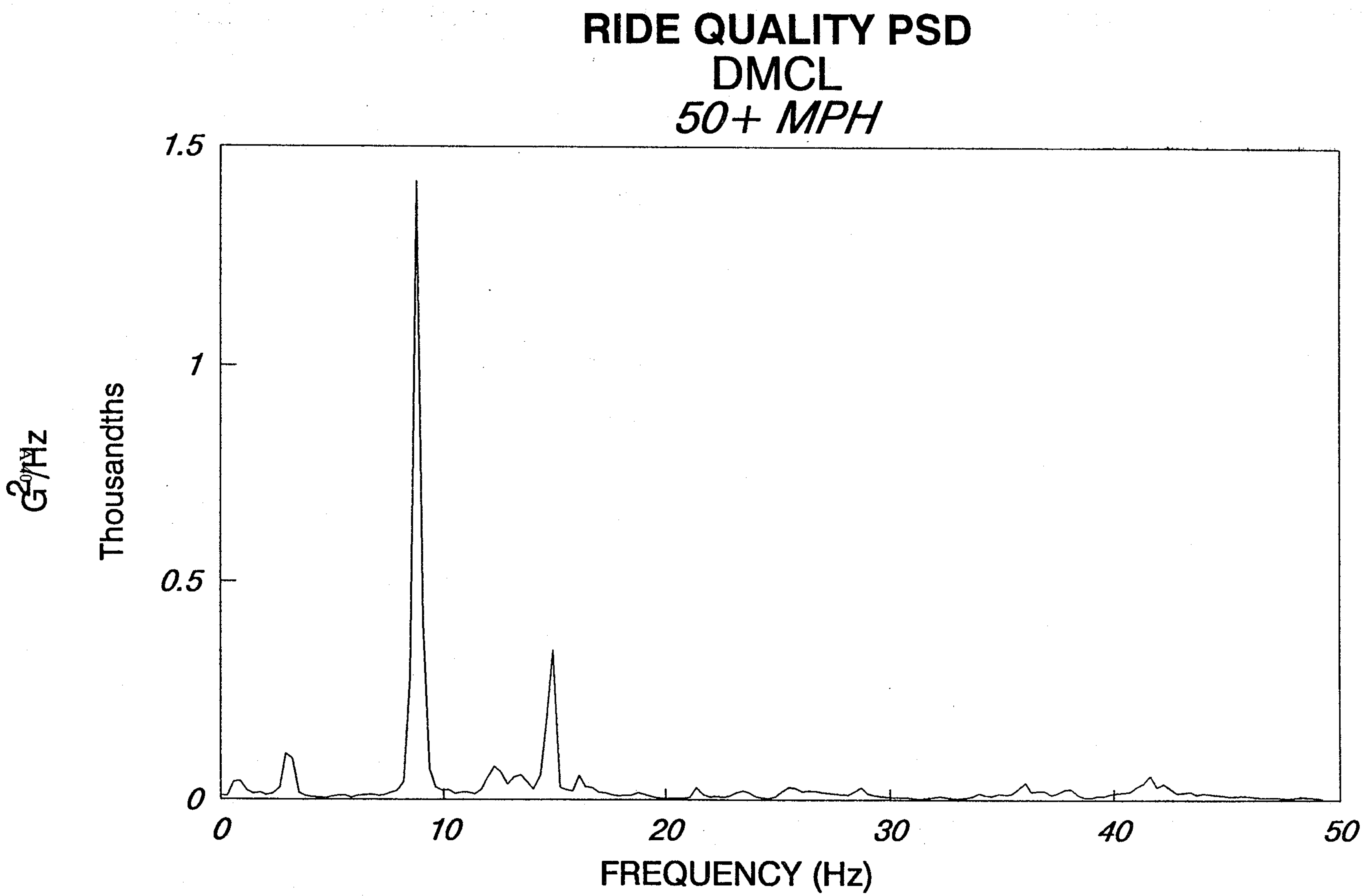


RMS = 0.036 G's
WEIGHT = 525,900 LBS.

RIDE QUALITY PSD
DMCV
50+ MPH



RMS = 0.192 G's
WEIGHT = 525,900 LBS.

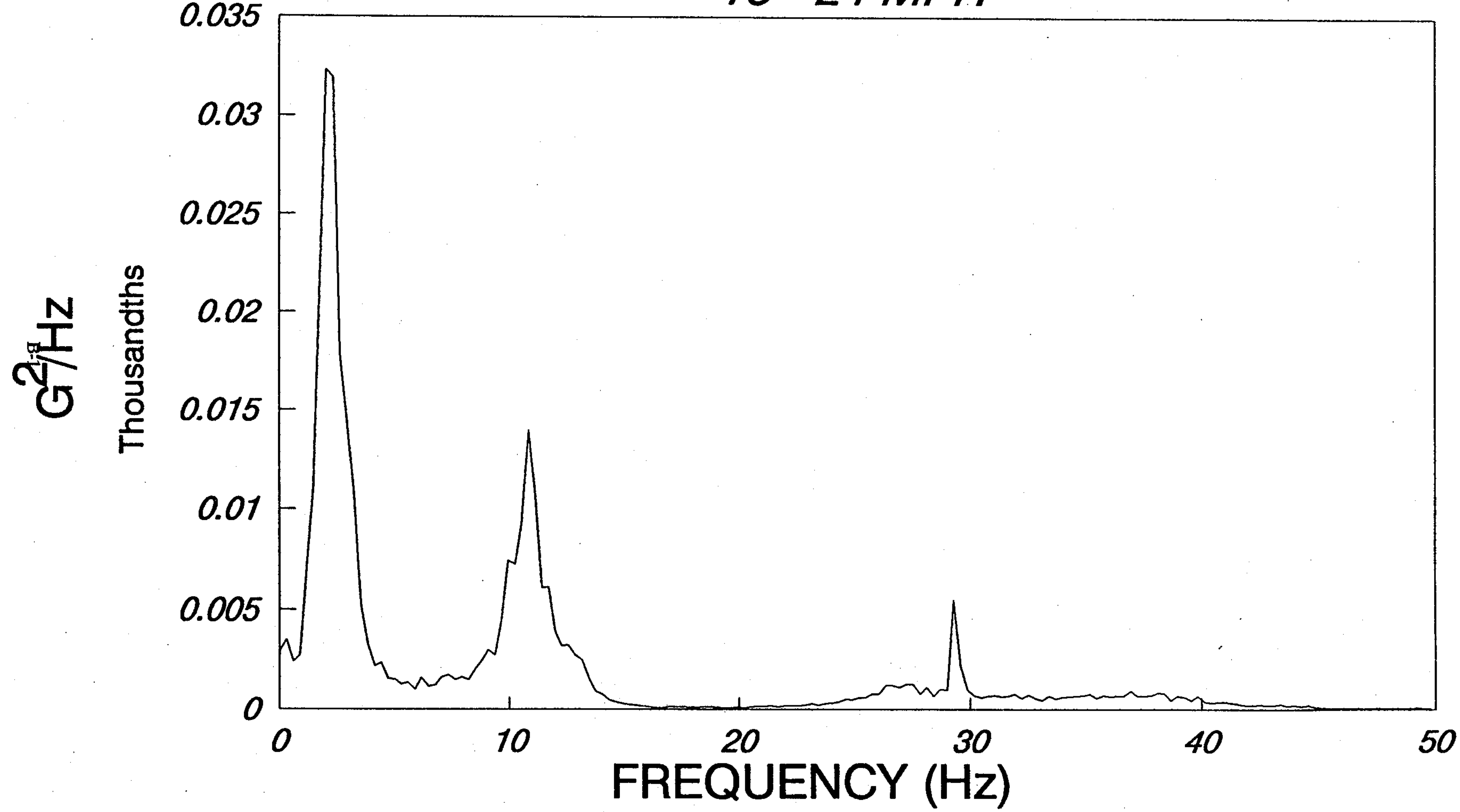


RMS = 0.050 G's
WEIGHT = 525,900 LBS.

Appendix B

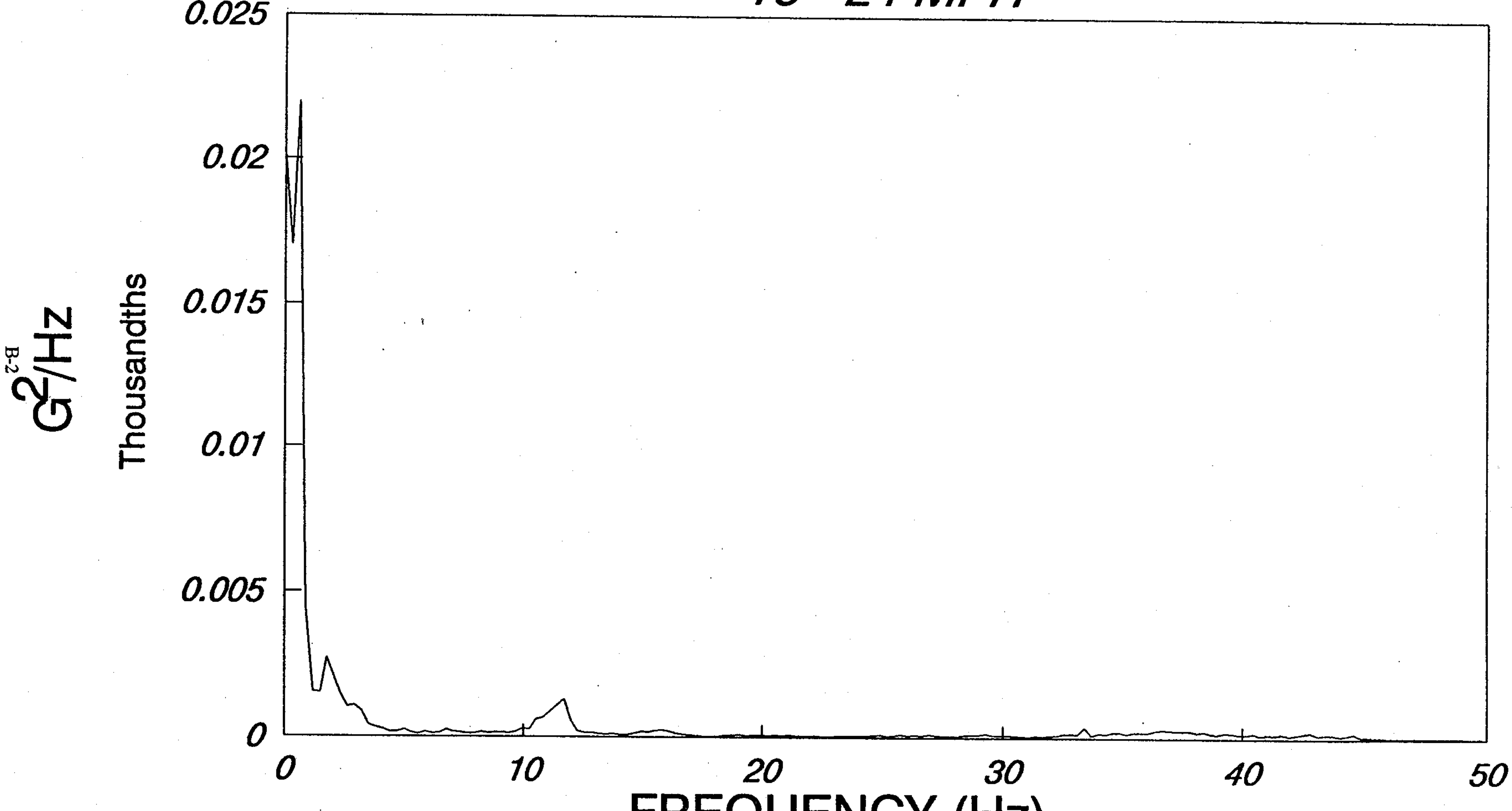
Empty Tank Car and Passenger Car PSD

RIDE QUALITY PSD
AMCV
15 - 24 MPH

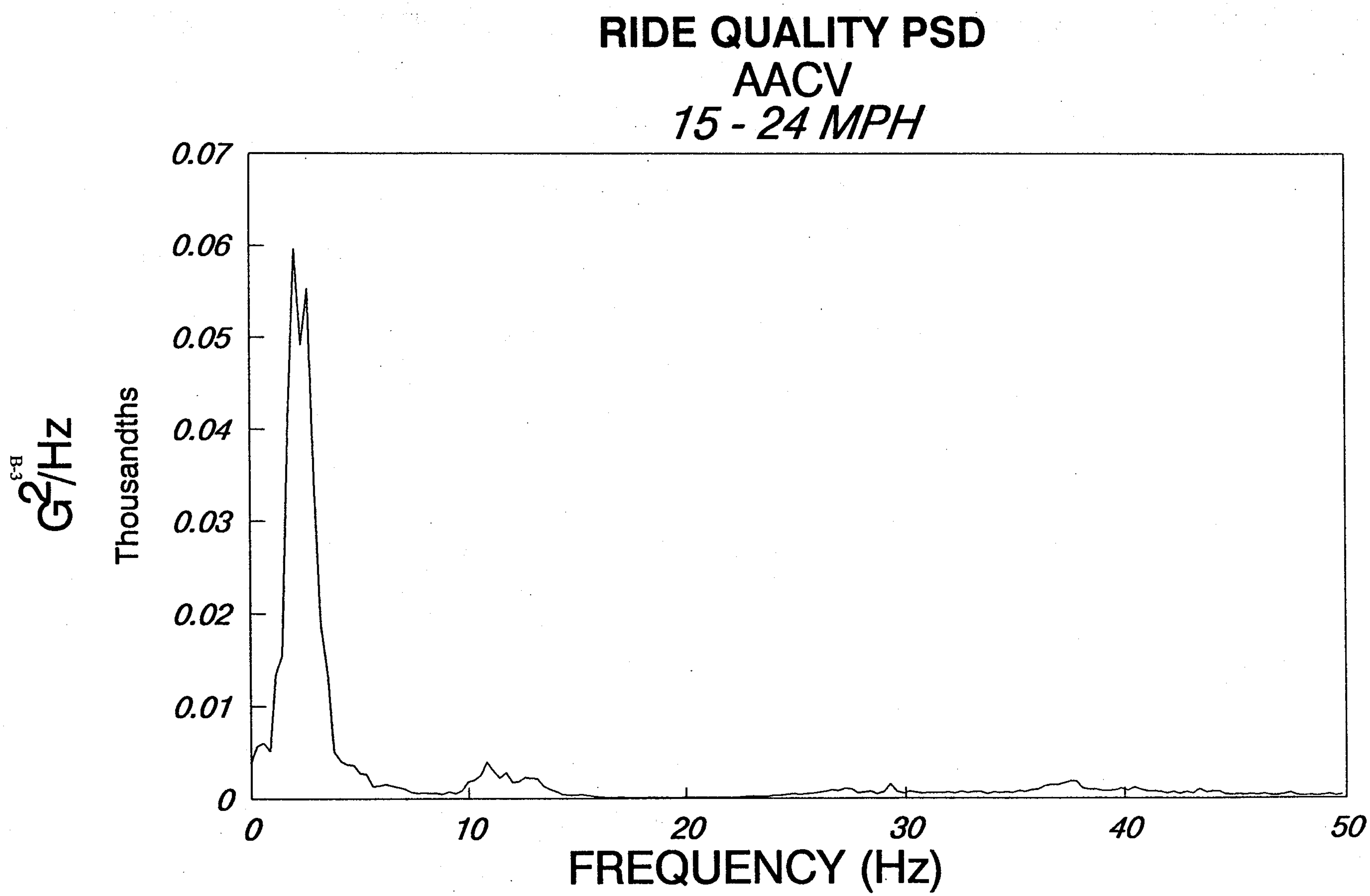


RMS = 0.015 G's
WEIGHT = 166,000 LBS.

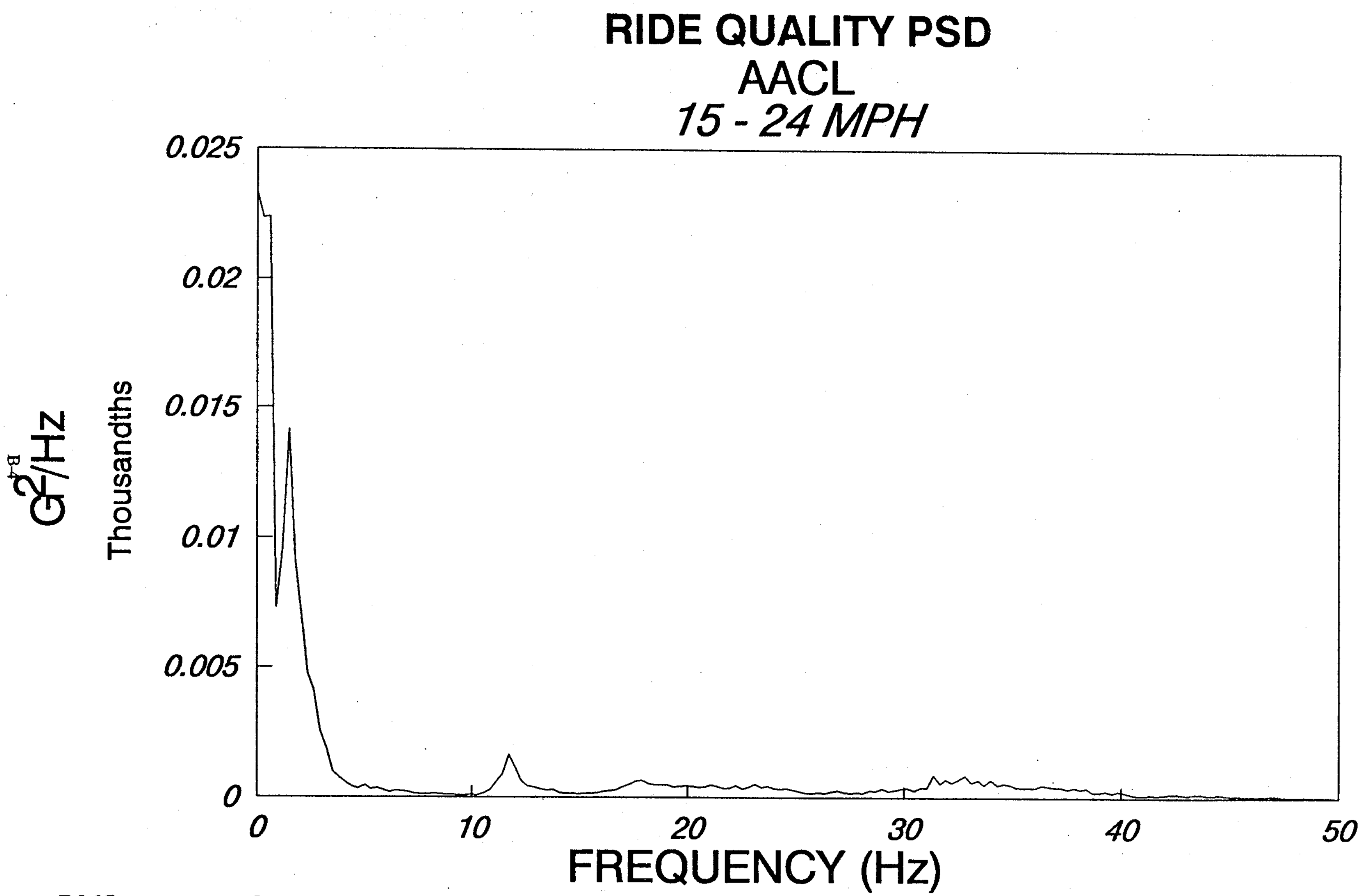
RIDE QUALITY PSD
AMCL
15 - 24 MPH



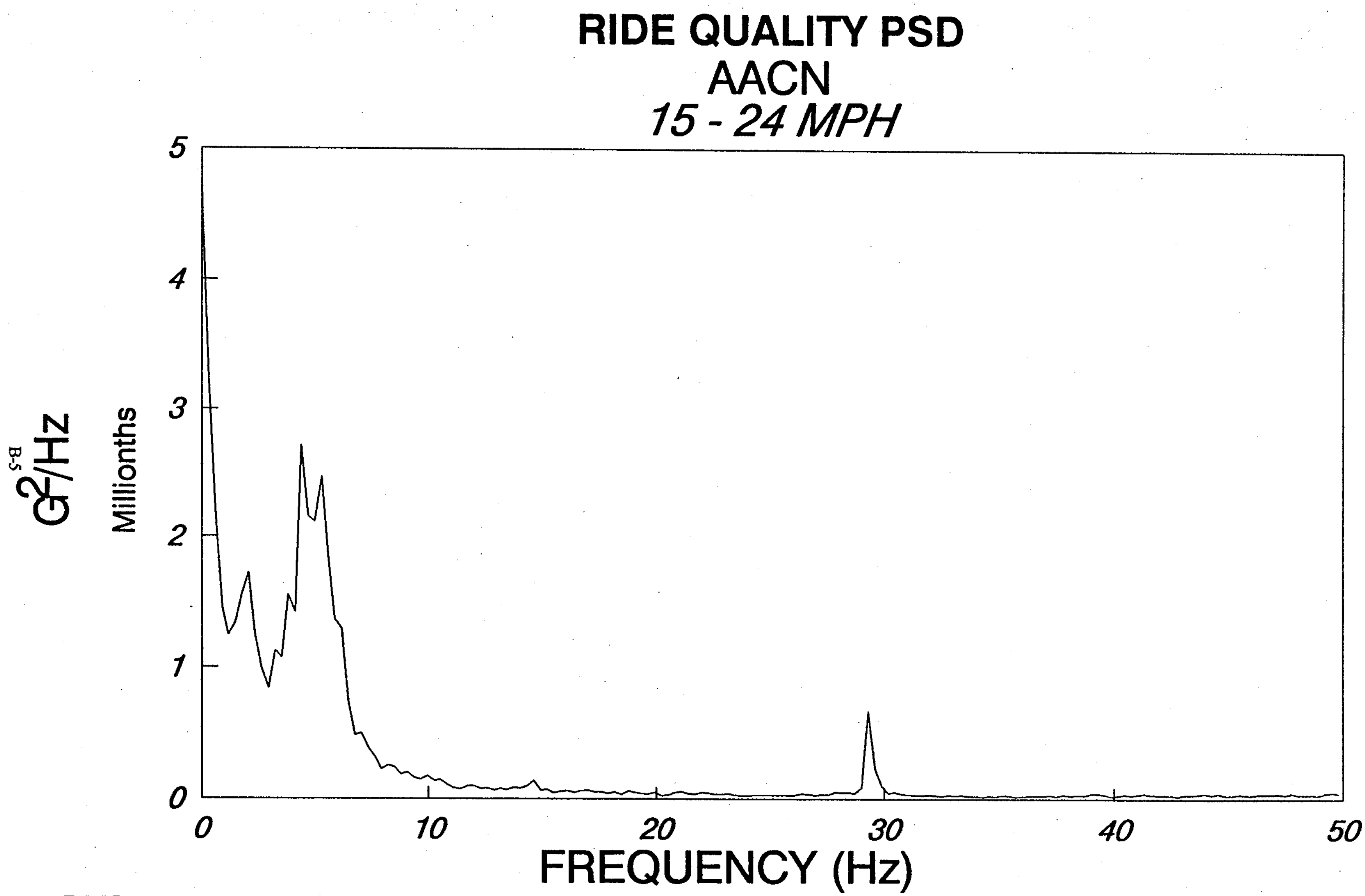
RMS = 0.018 G's
WEIGHT = 166,000 LBS.



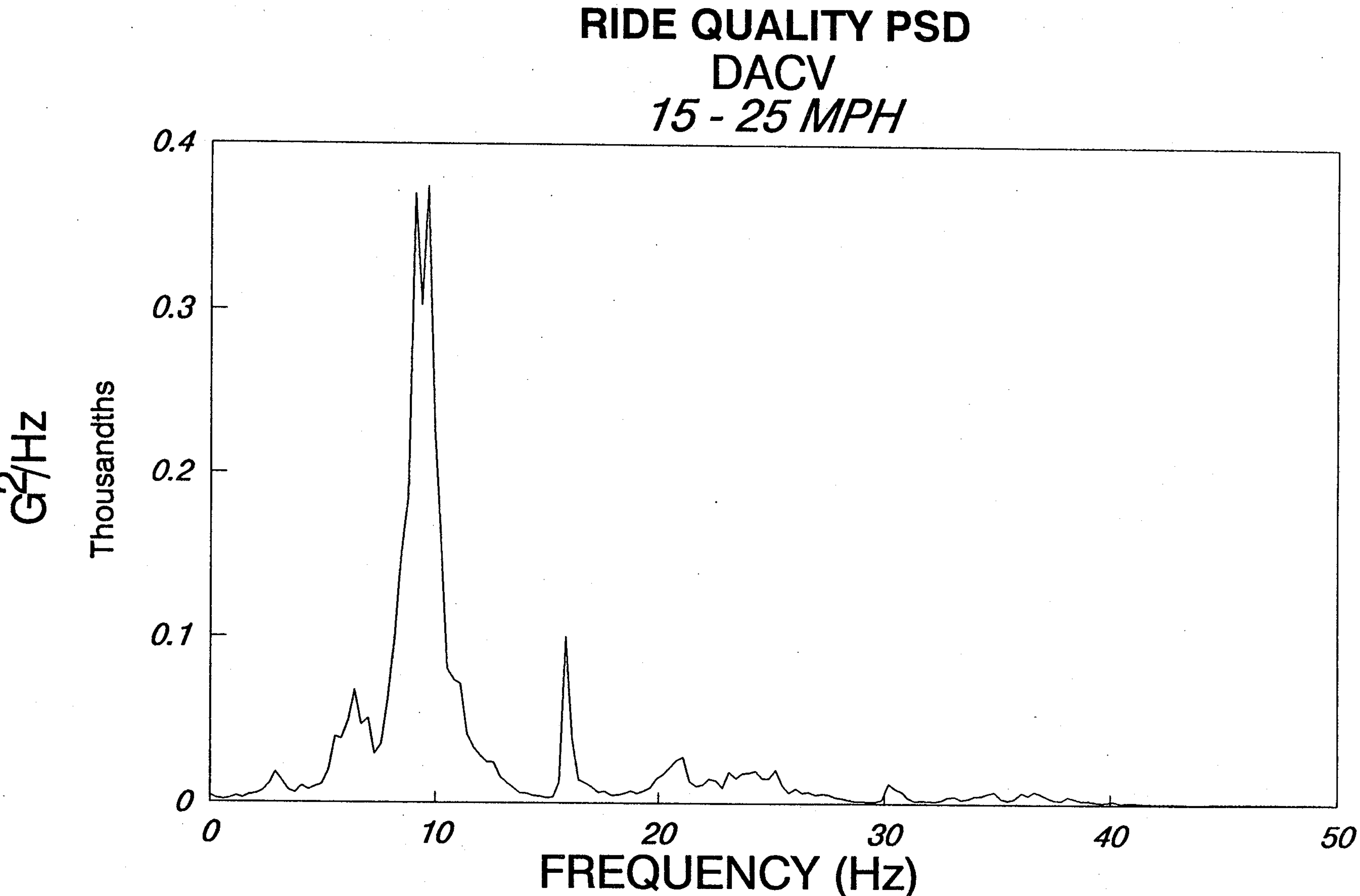
RMS = 0.015 G's
WEIGHT = 166,000 LBS.



RMS = 0.021 G's
WEIGHT = 166,000 LBS.

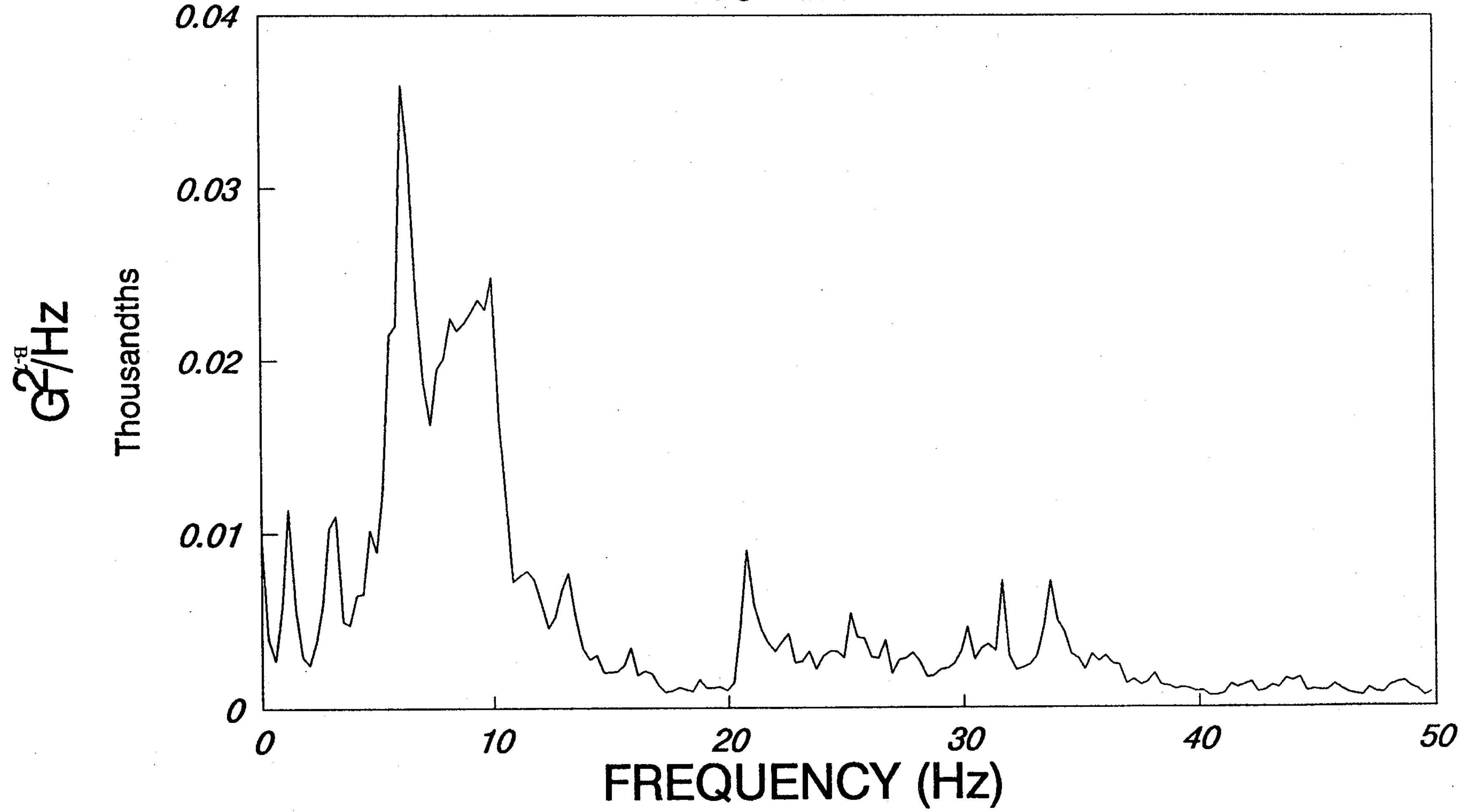


RMS = 0.012 G's
WEIGHT = 166,000 LBS.

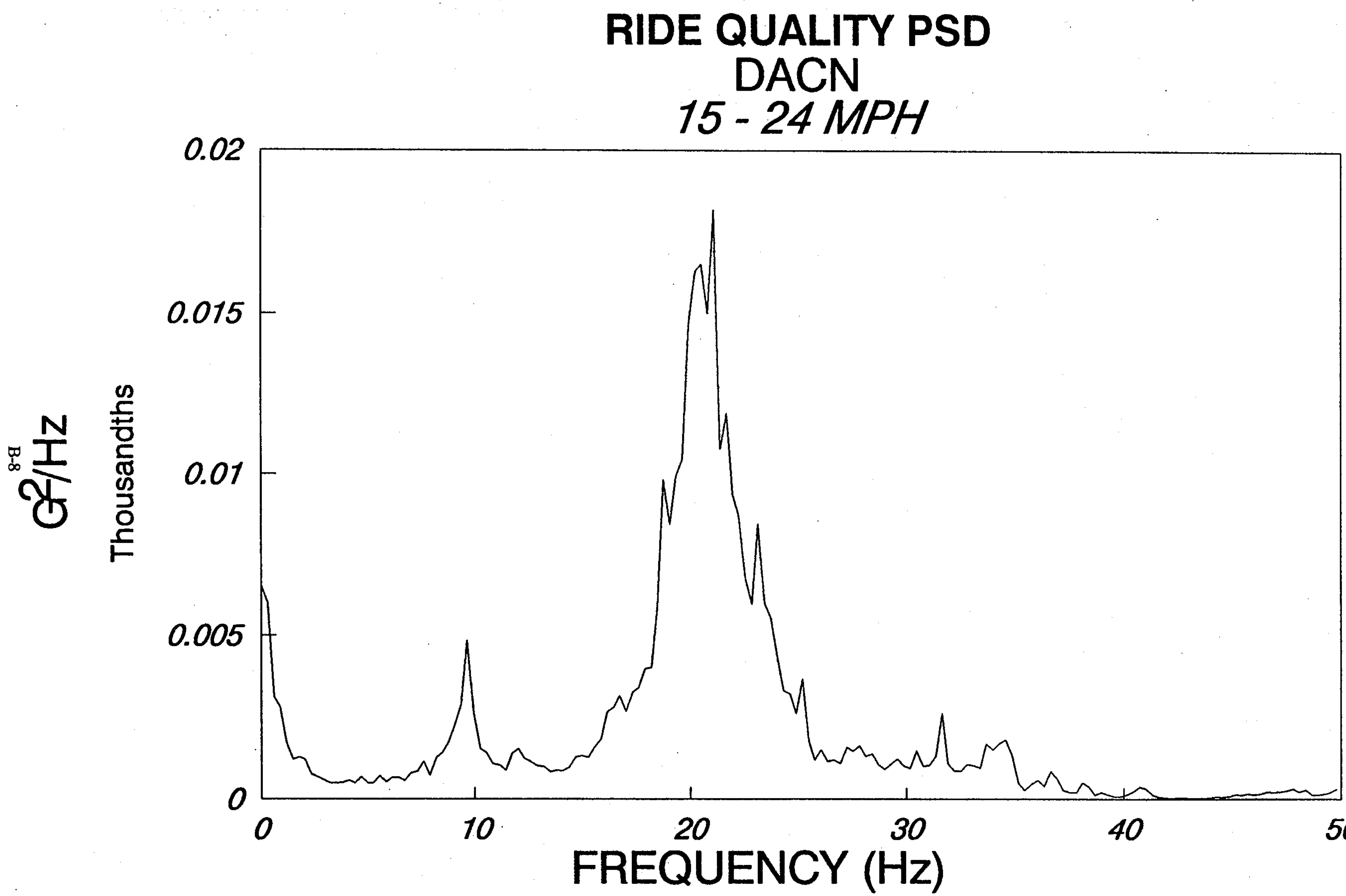


RMS = 0.037 G's
WEIGHT = 133,000 LBS.

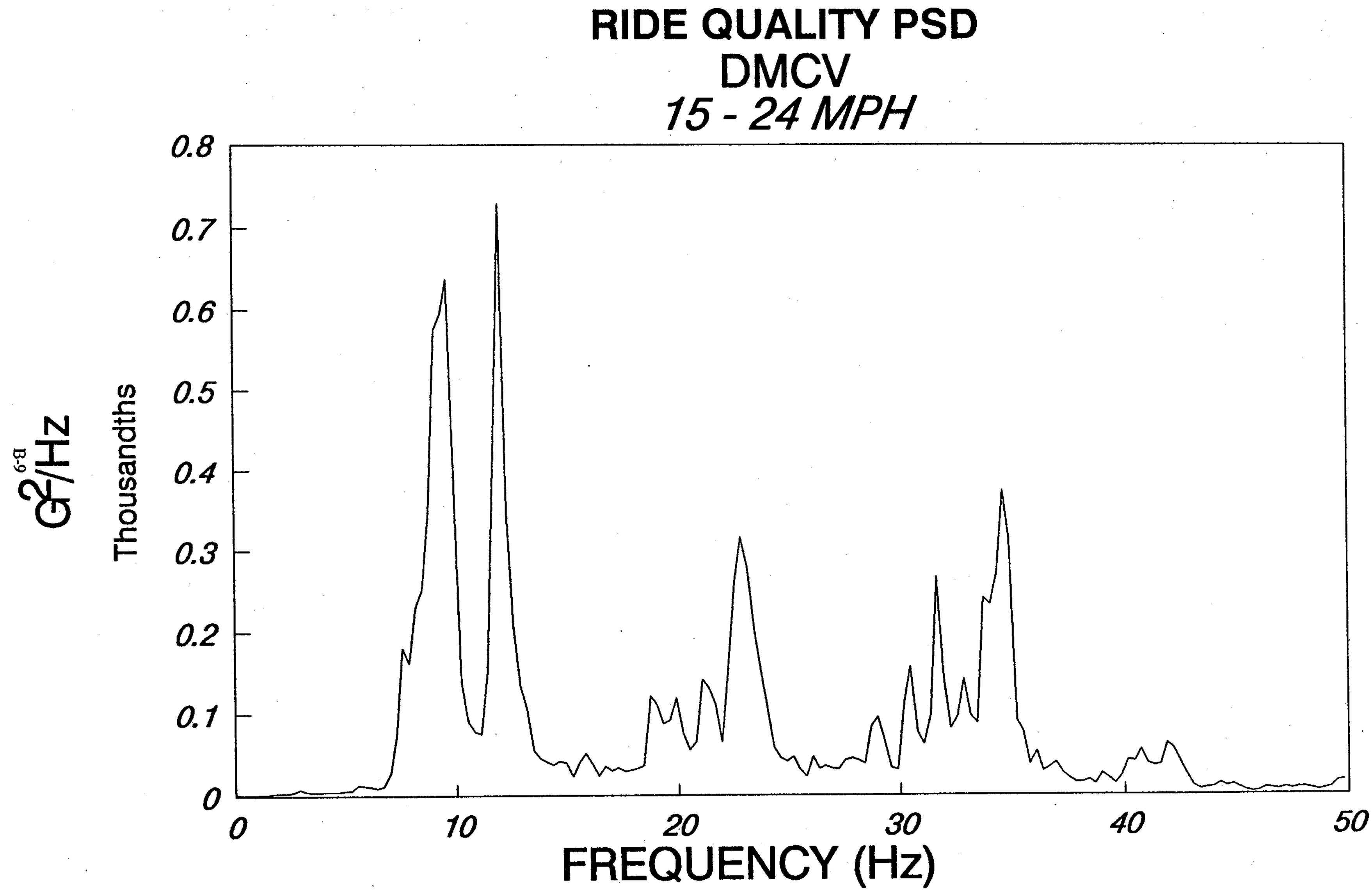
RIDE QUALITY PSD
DACL
15 - 24 MPH



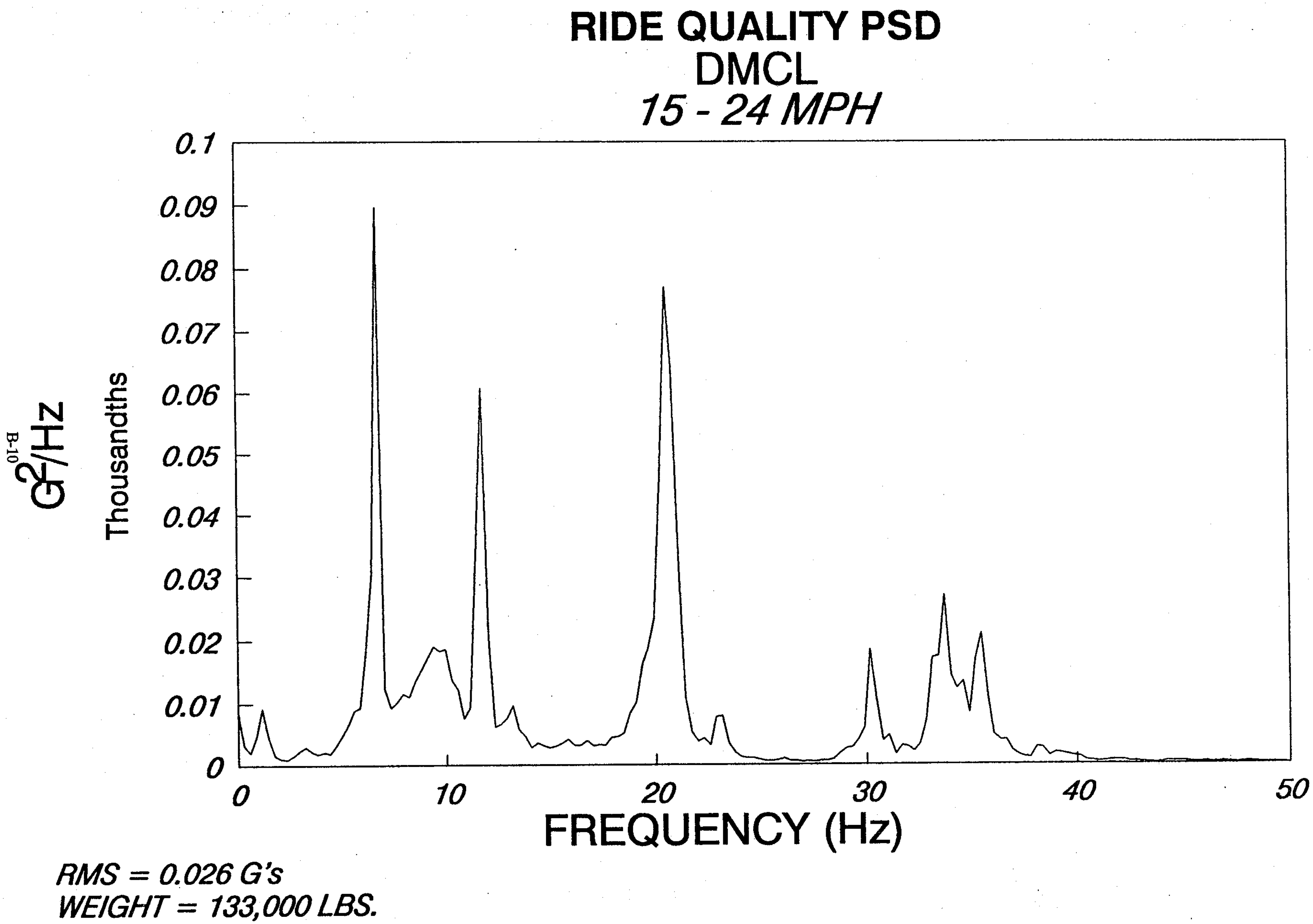
RMS = 0.025 G's
WEIGHT = 133,000 LBS.

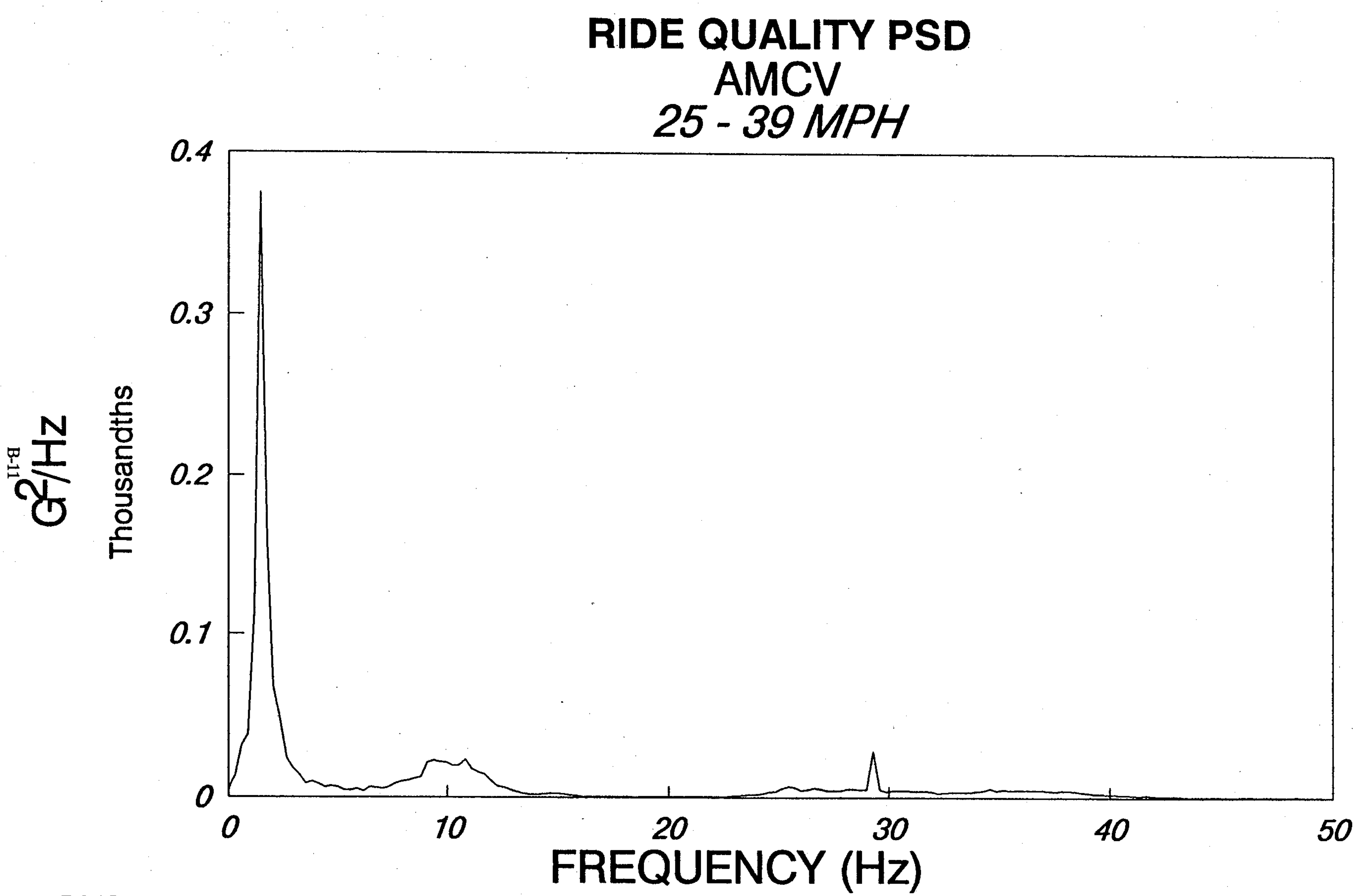


RMS = 0.018 G's
WEIGHT = 133,000 LBS.



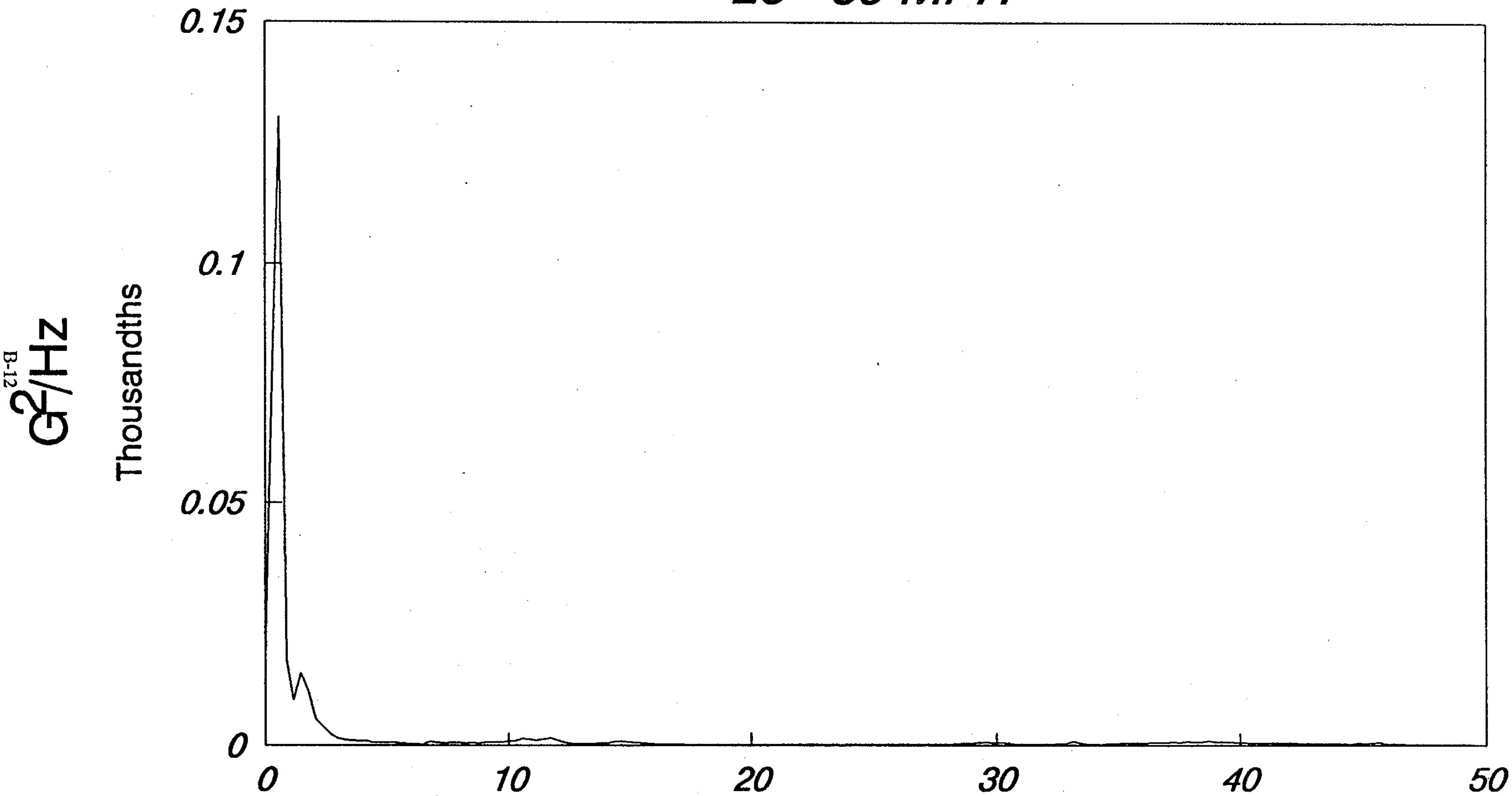
RMS = 0.069 G's
WEIGHT = 133,000 LBS.


RIDE QUALITY PSD
DMCL
15 - 24 MPH
G2/Hz
Thousandths
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.026 G's
WEIGHT = 133,000 LBS.

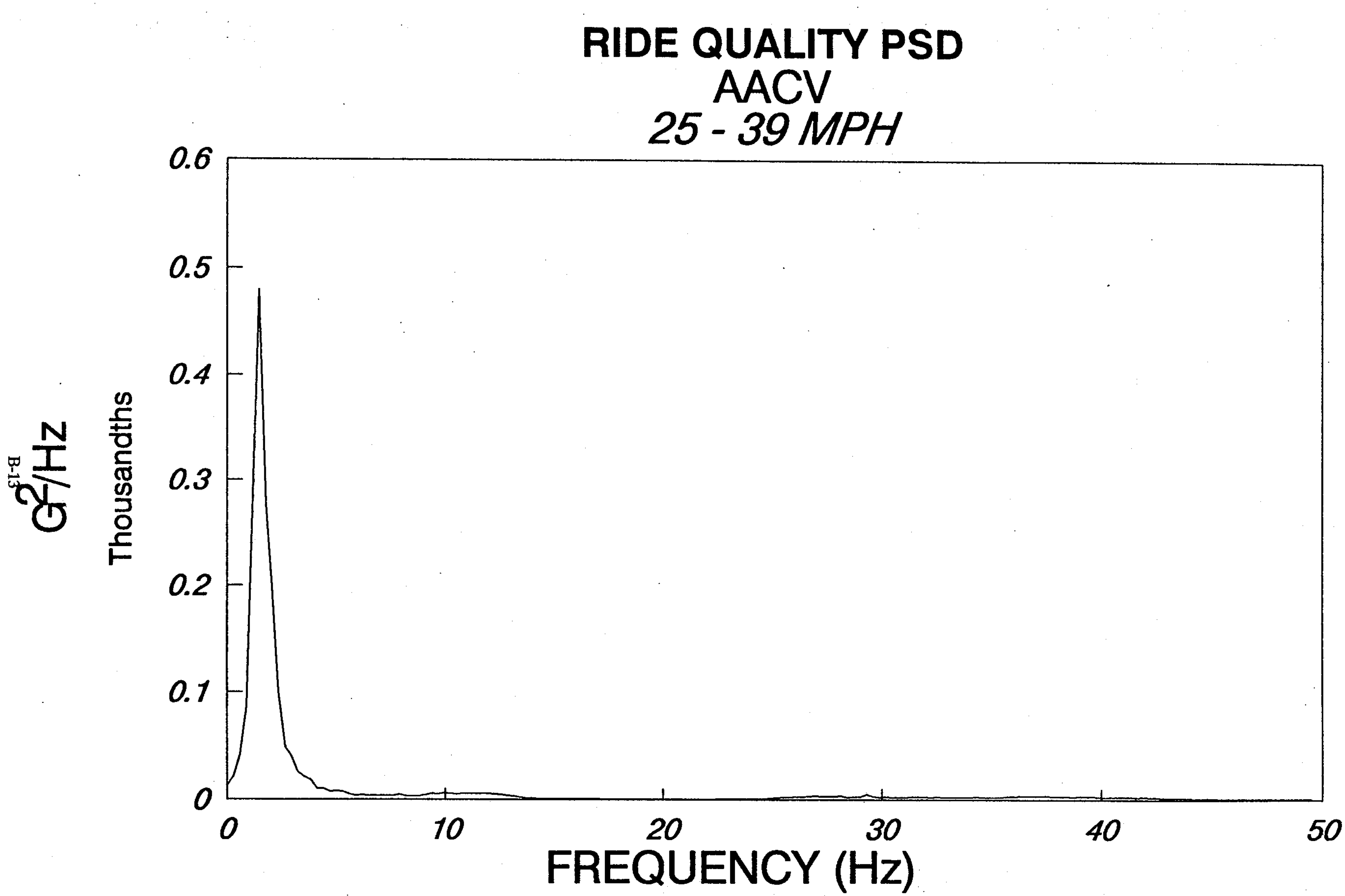


RMS = 0.024 G's
WEIGHT = 166,000 LBS.

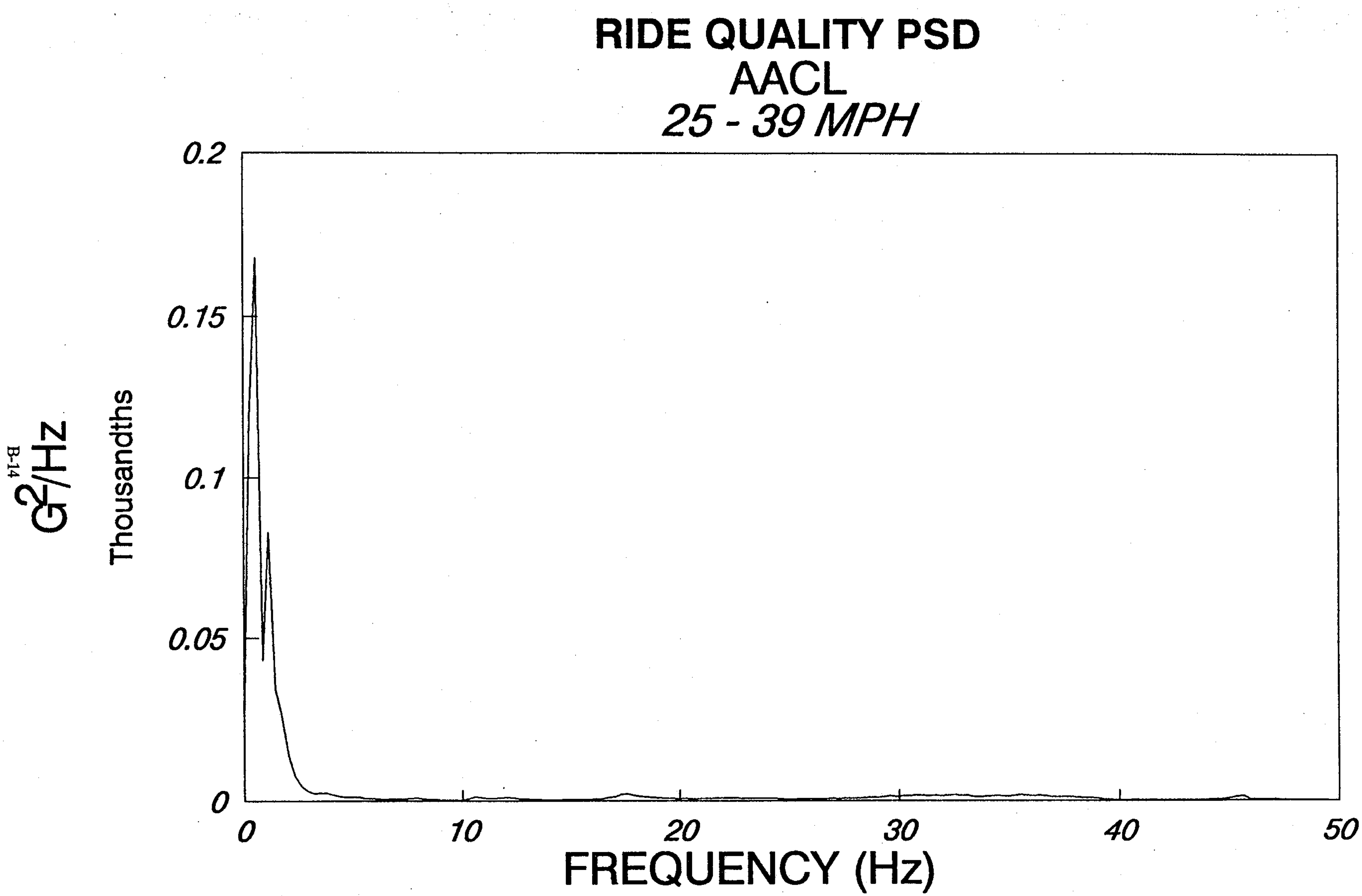
RIDE QUALITY PSD
AMCL
25 - 39 MPH



RMS = 0.022 G's
WEIGHT = 166,000 LBS.

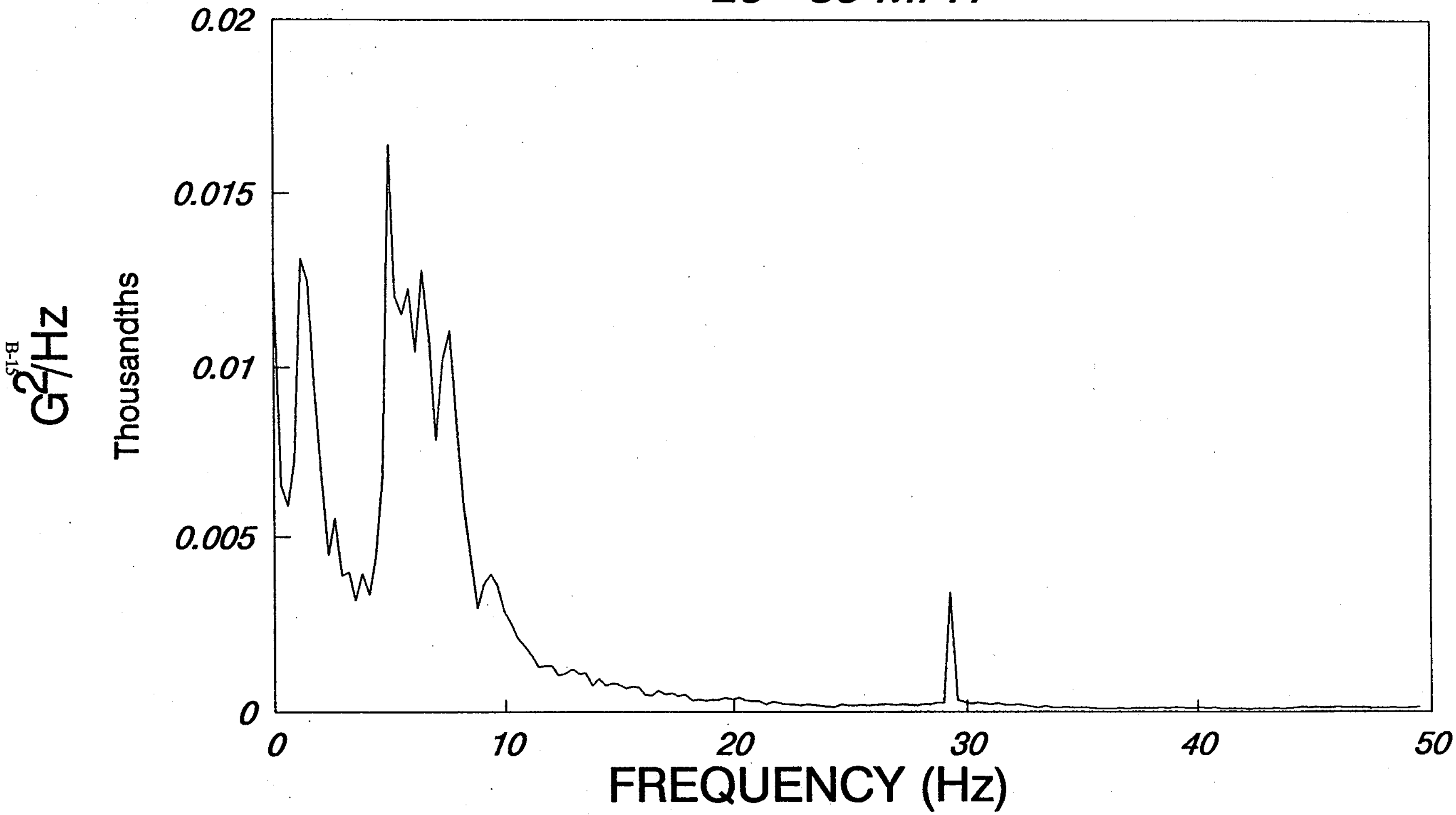


RMS = 0.026 G's
WEIGHT = 166,000 LBS.

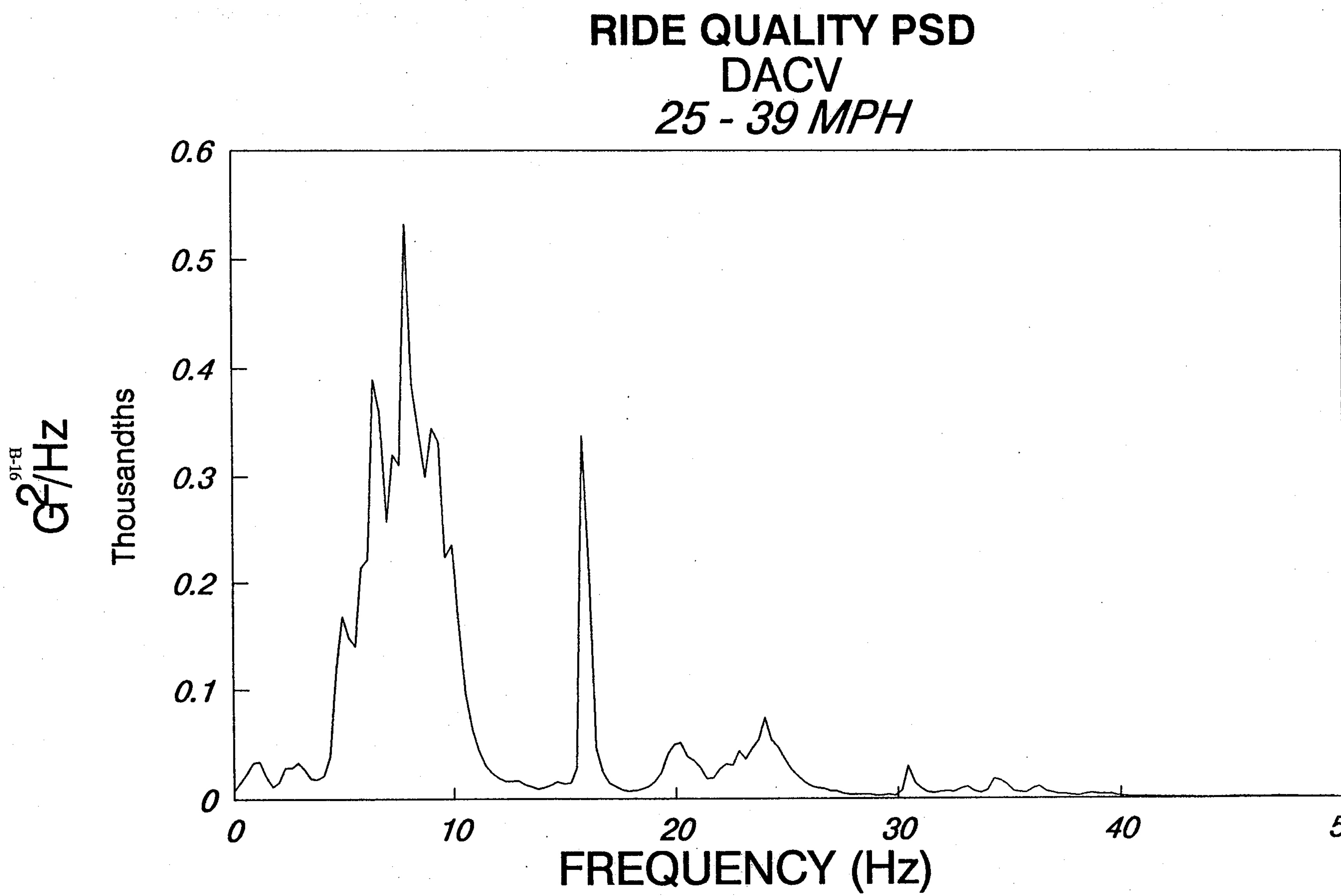


RMS = 0.030 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD
AACN
25 - 39 MPH

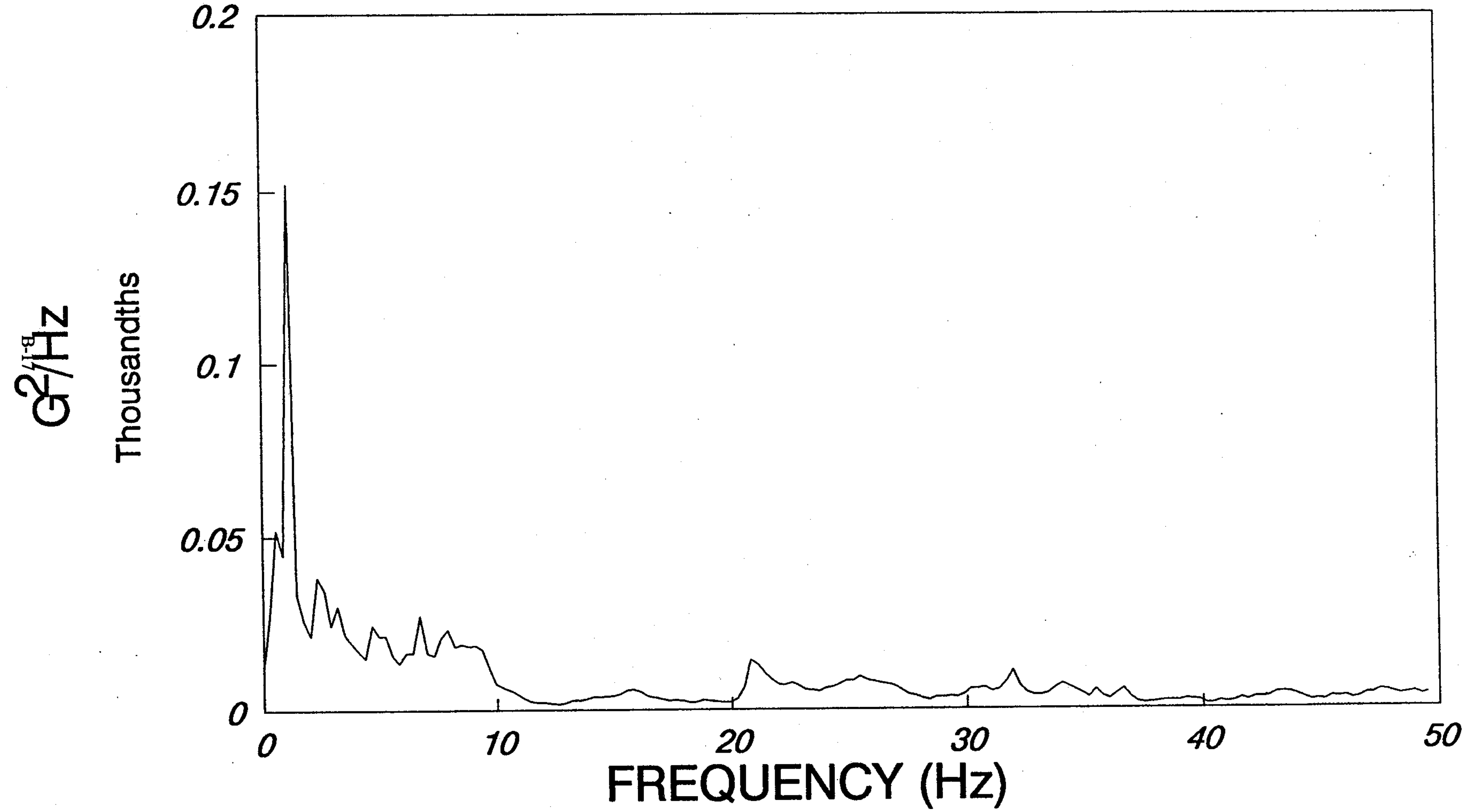


RMS = 0.016 G's
WEIGHT = 166,000 LBS.

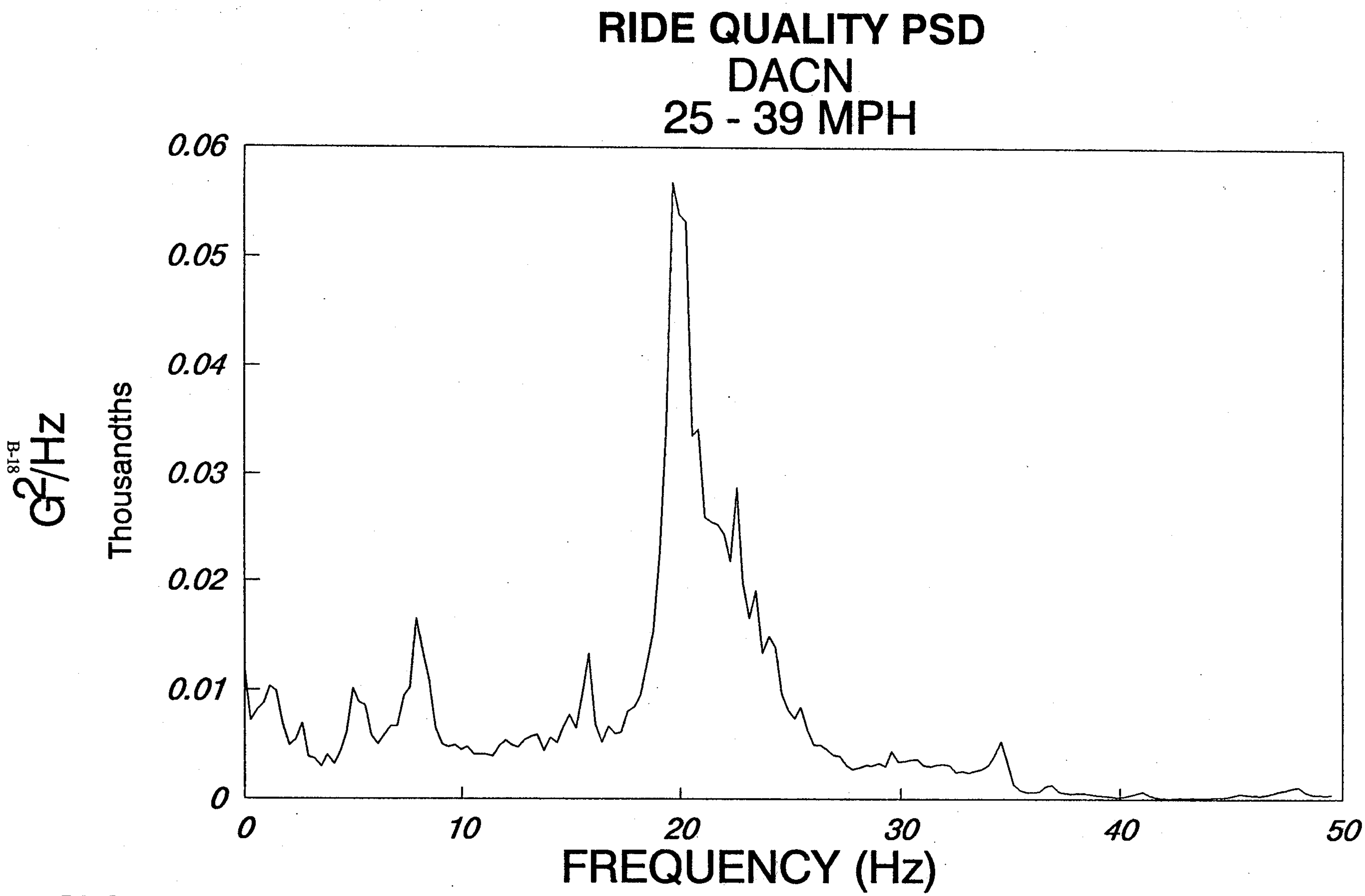


RMS = 0.051 G's
WEIGHT = 133,000 LBS.

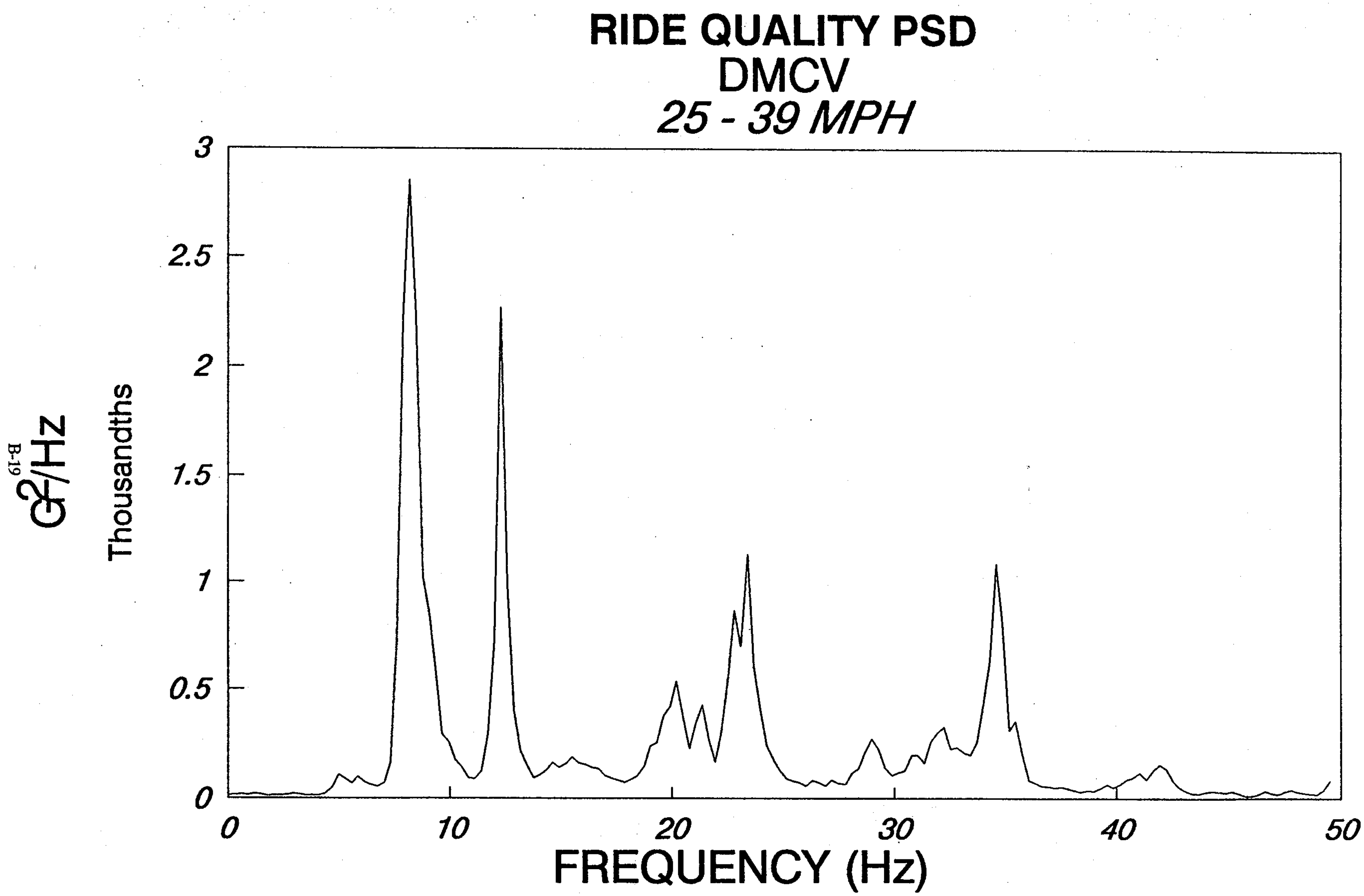
RIDE QUALITY PSD
DACL
25 - 39 MPH



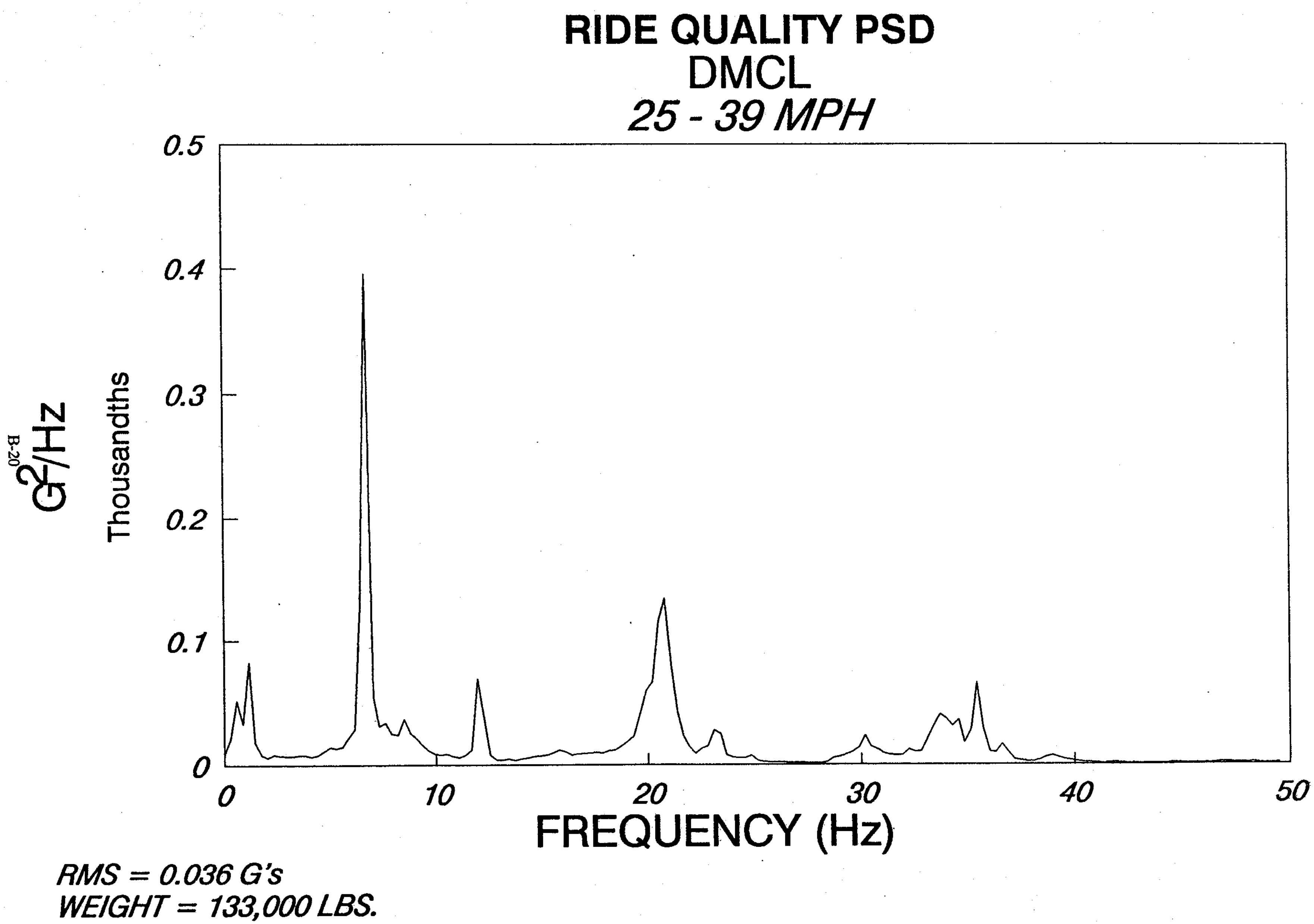
RMS = 0.029 G's
WEIGHT = 133,000 LBS.



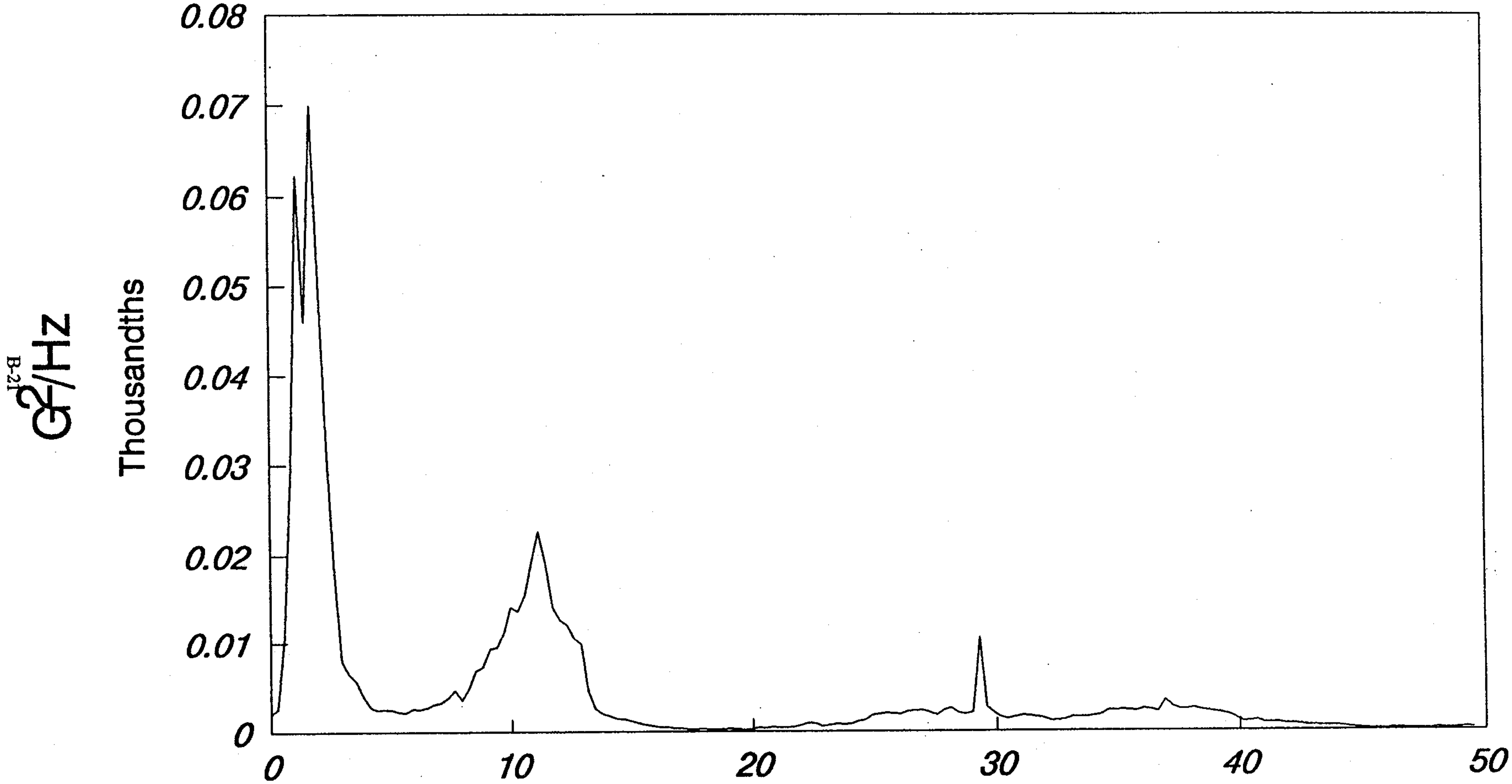
RMS = 0.023 G's
WEIGHT = 133,000 LBS.



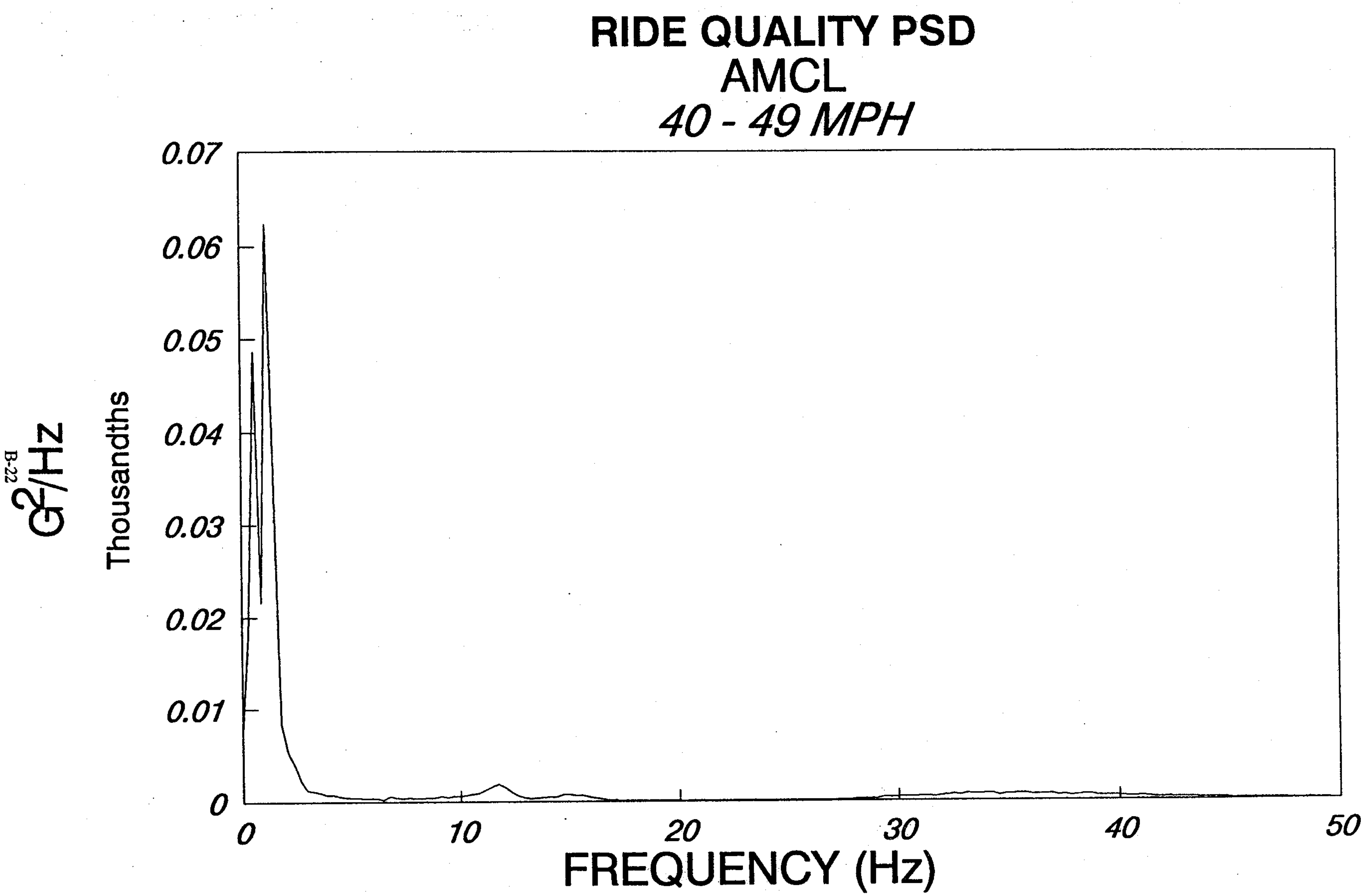
RMS = 0.117 G's
WEIGHT = 133,000 LBS.


RIDE QUALITY PSD
DMCL
25 - 39 MPH
G²/Hz
Thousandths
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.036 G's
WEIGHT = 133,000 LBS.

RIDE QUALITY PSD
AMCV
40 - 49 MPH



RMS = 0.018 G's
WEIGHT = 166,000 LBS.

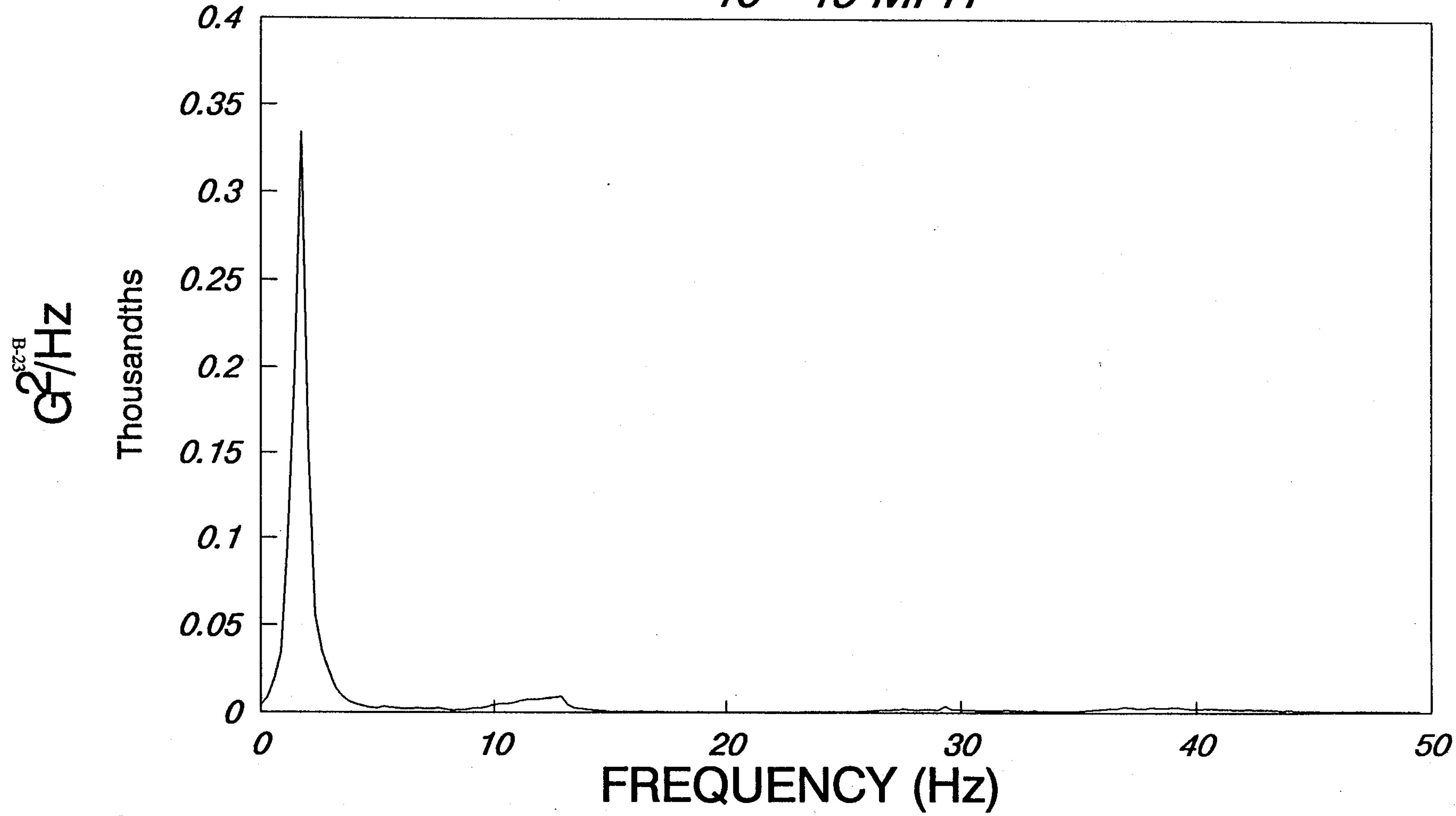


RMS = 0.011 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD

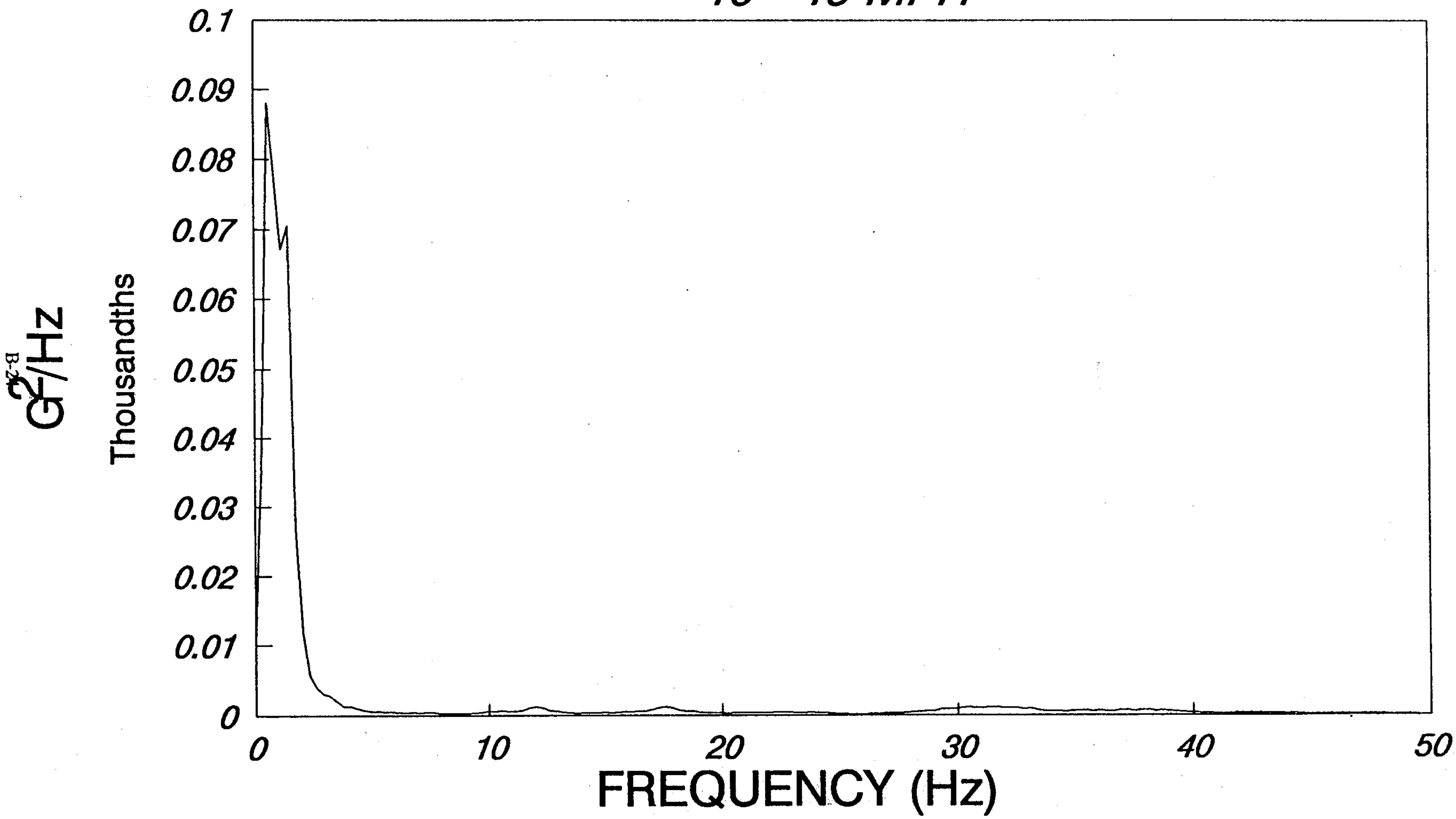
AACV

40 - 49 MPH

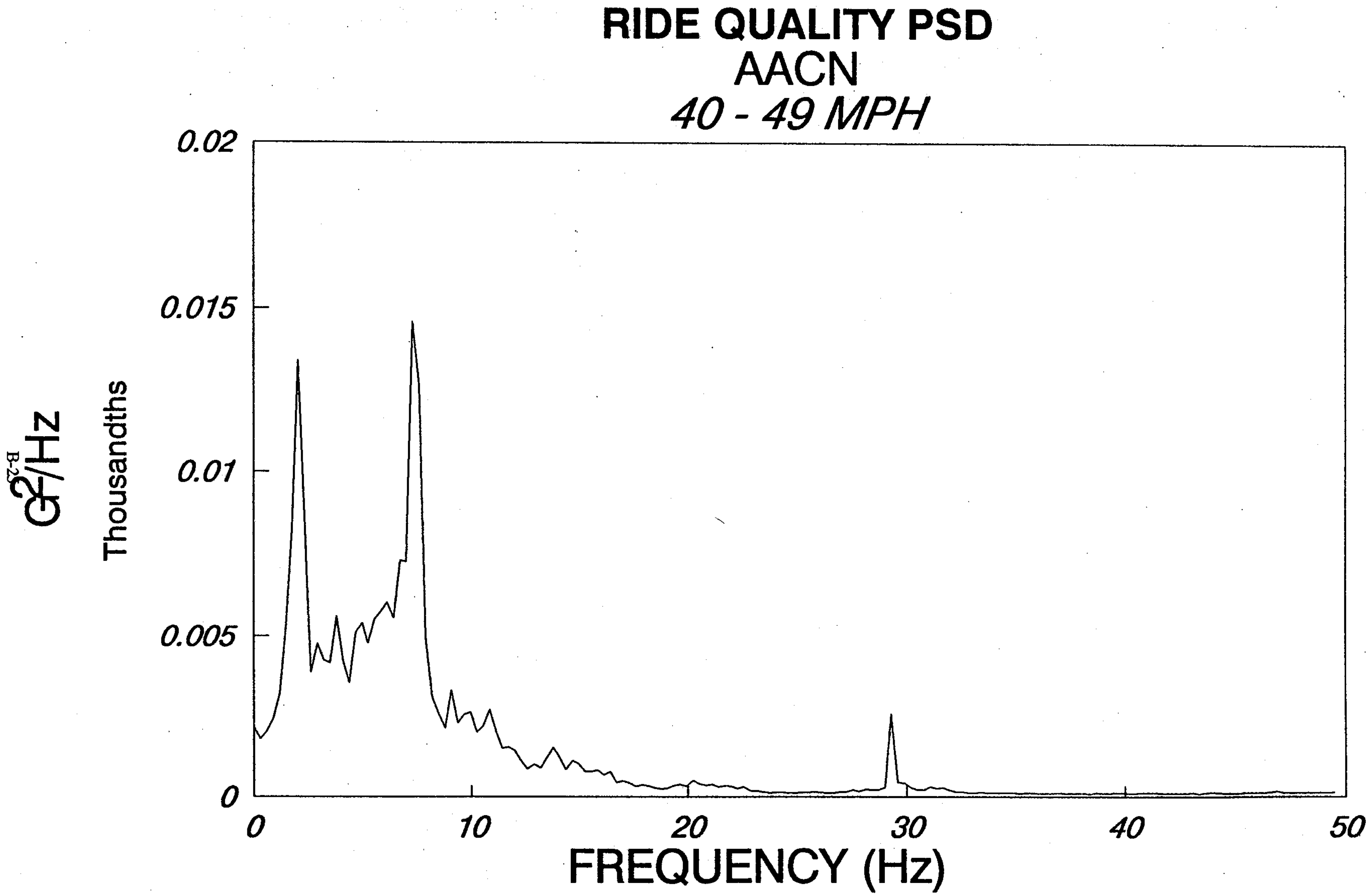


RMS = 0.021 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD
AACL
40 - 49 MPH

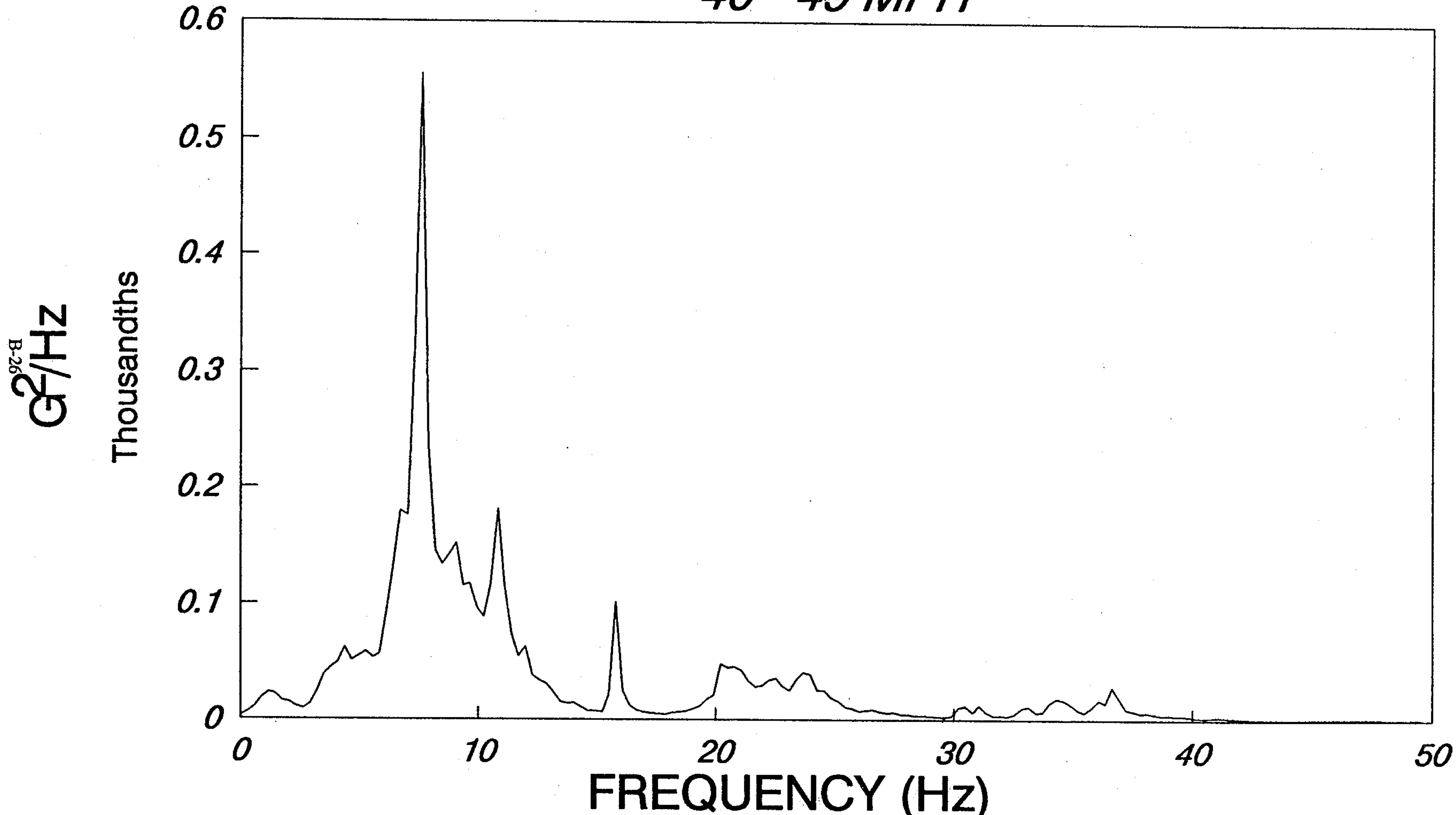


RMS = 0.023 G's
WEIGHT = 166,000 LBS.



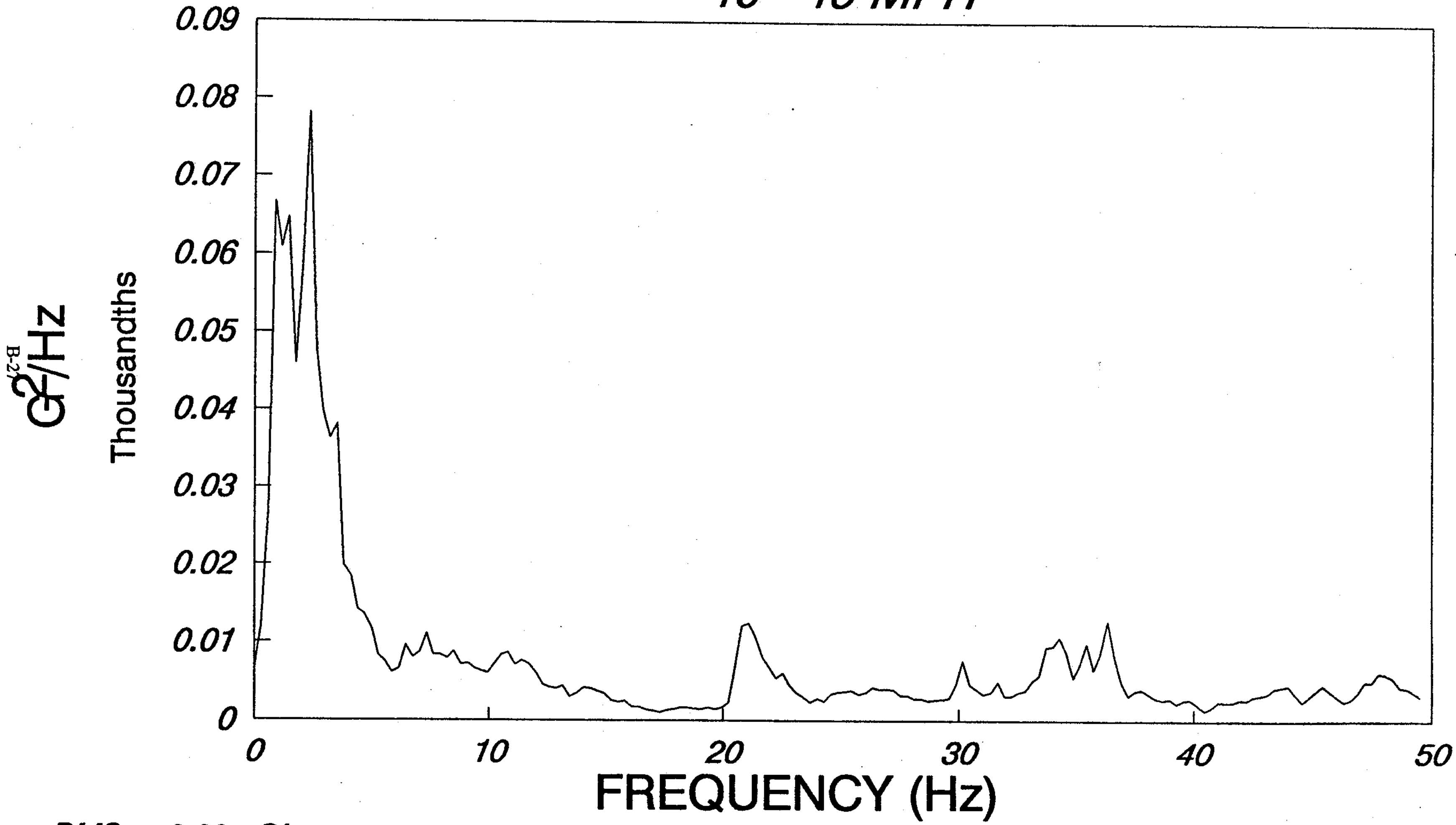
RMS = 0.014 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD
DACV
40 - 49 MPH

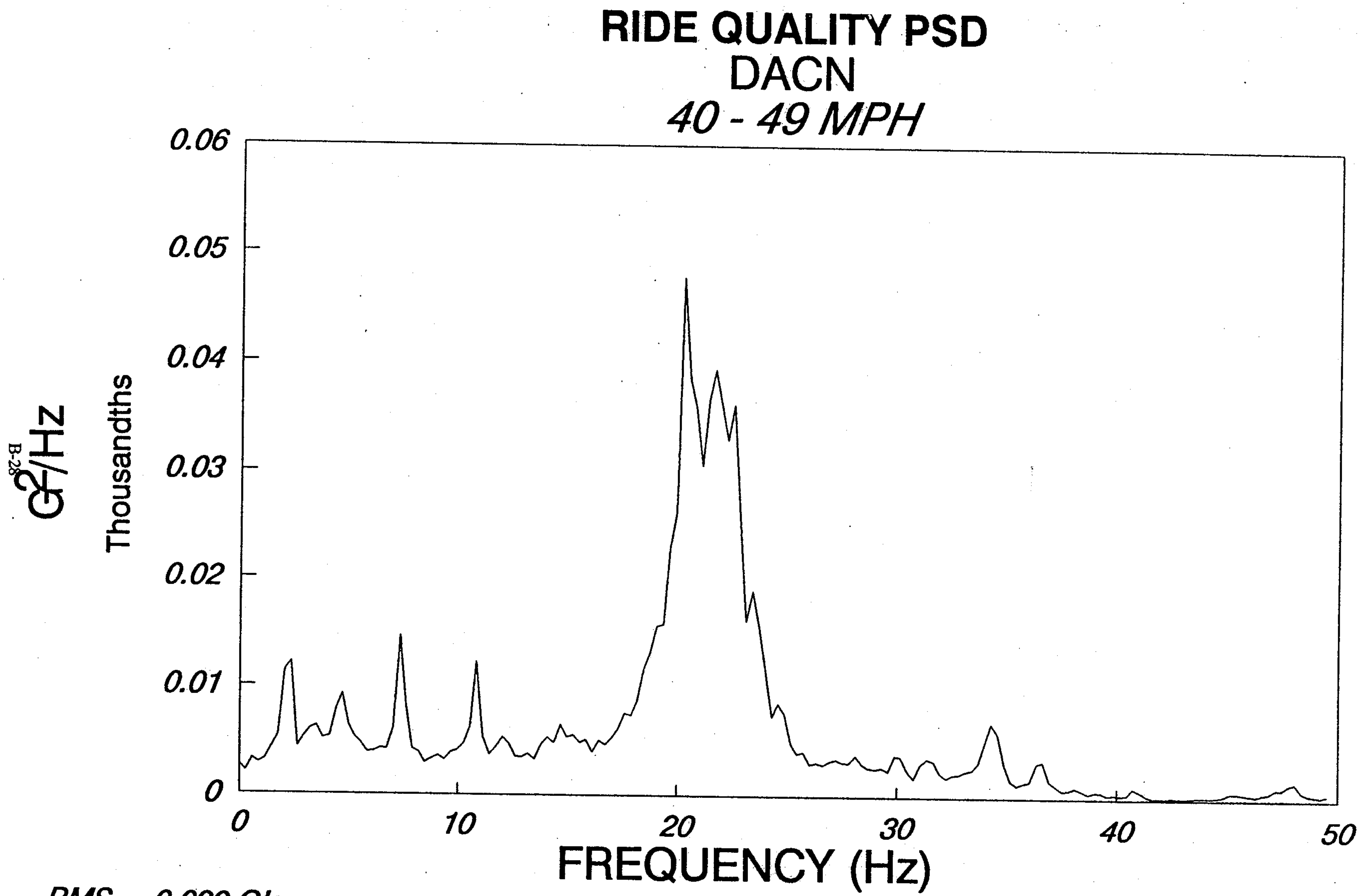


RMS = 0.042 G's
WEIGHT = 133,000 LBS.

RIDE QUALITY PSD
DACL
40 - 49 MPH

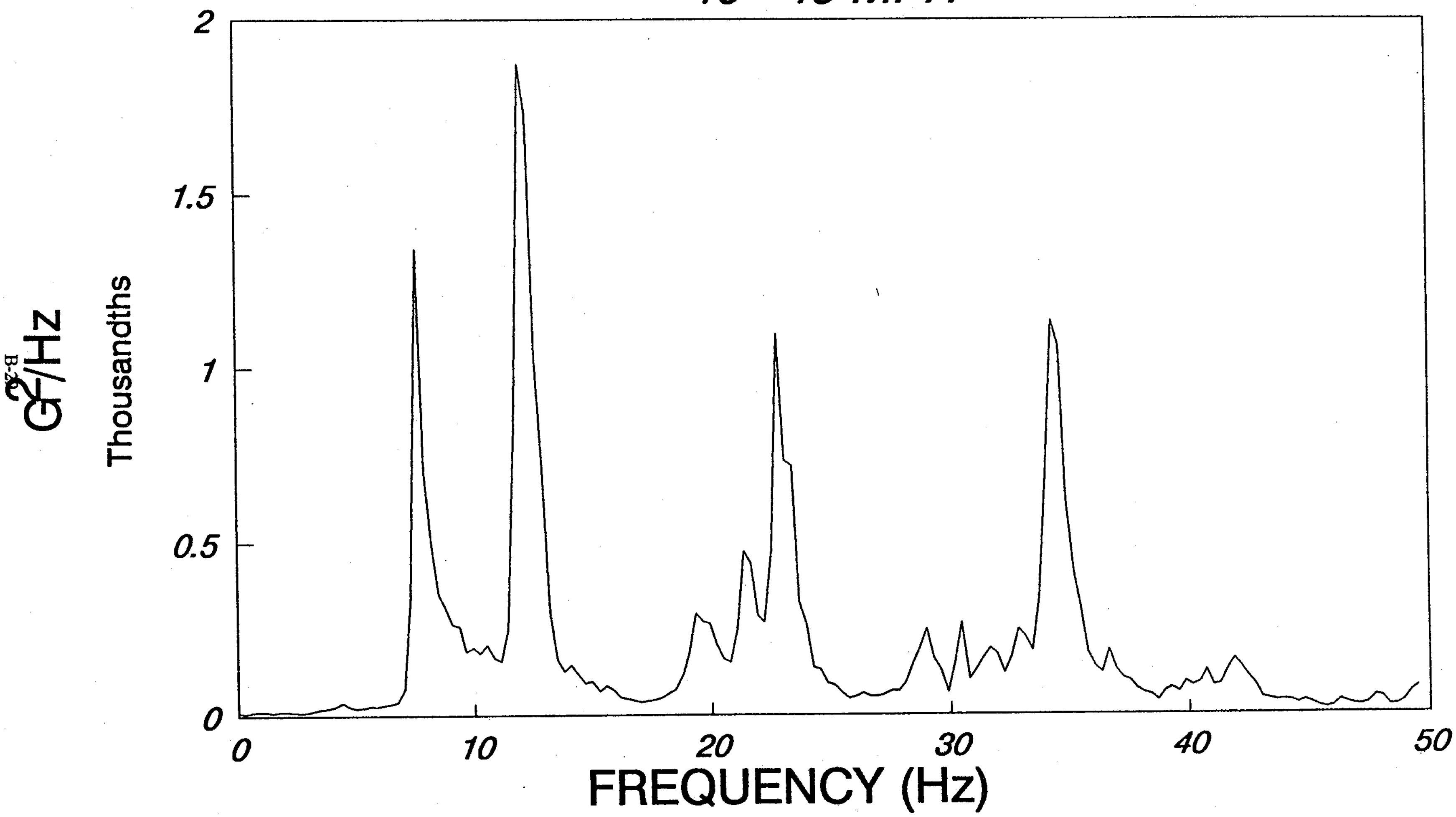


RMS = 0.024 G's
WEIGHT = 133,000 LBS.



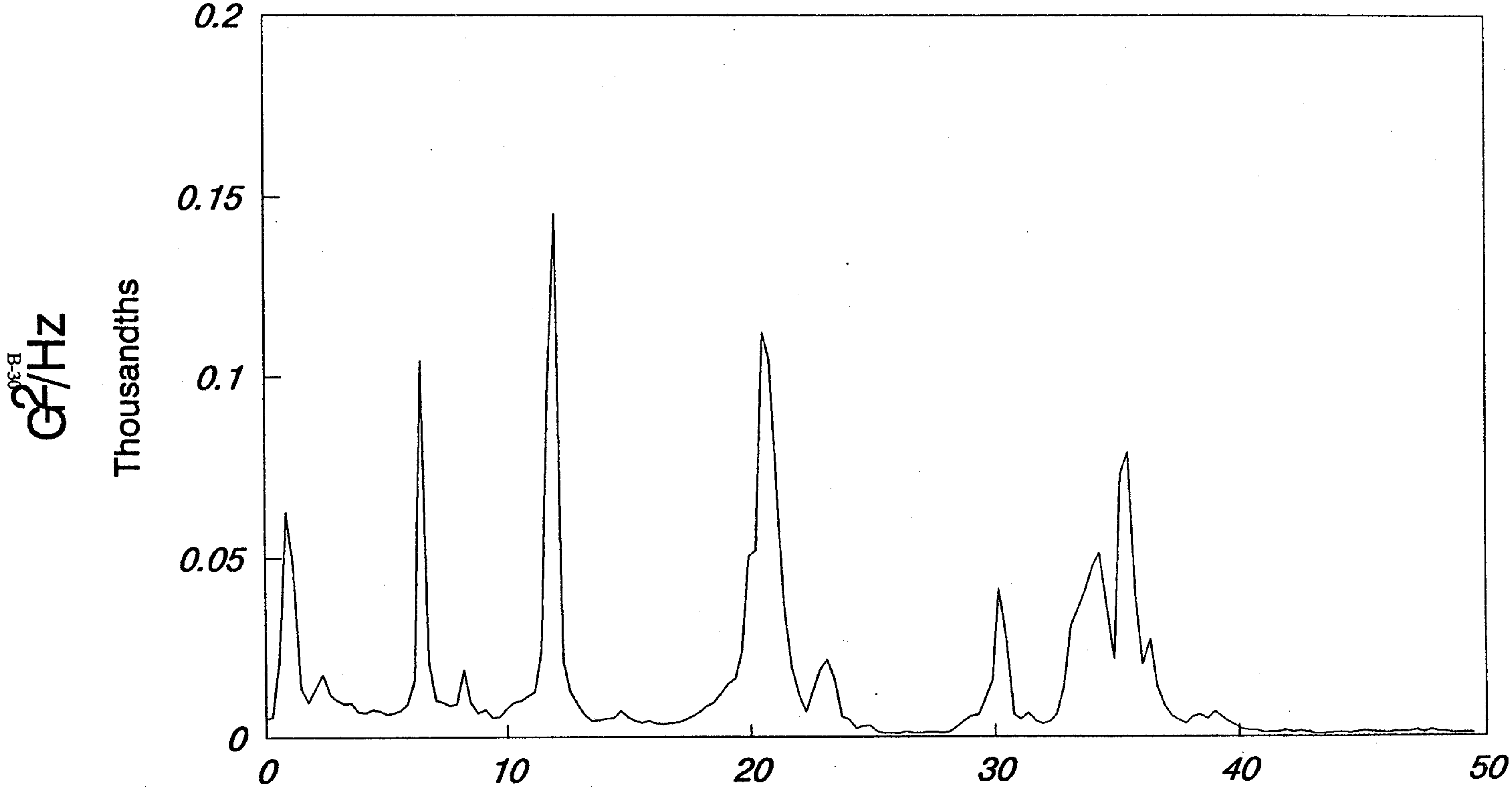
RMS = 0.022 G's
WEIGHT = 133,000 LBS.

RIDE QUALITY PSD
DMCV
40 - 49 MPH

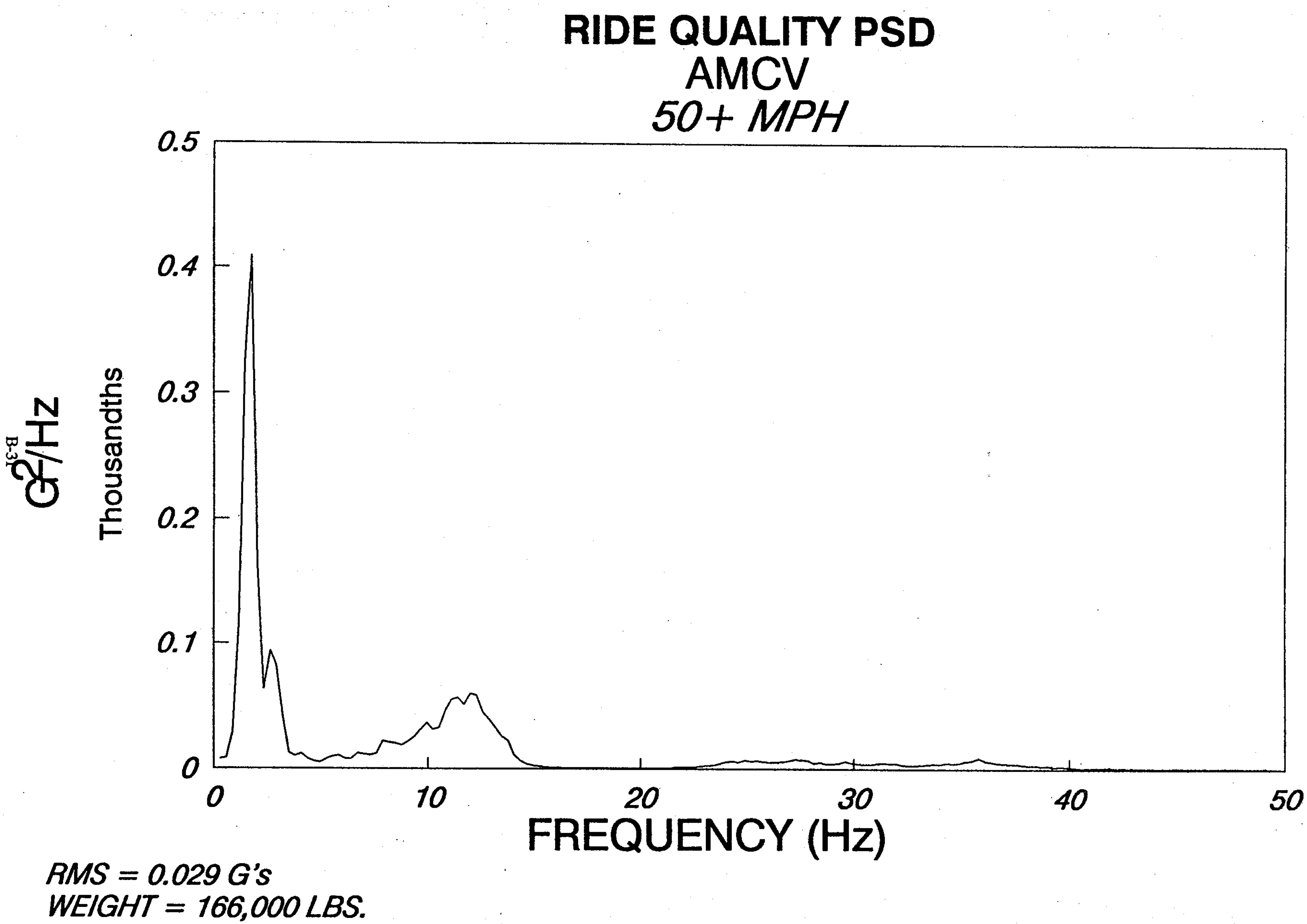


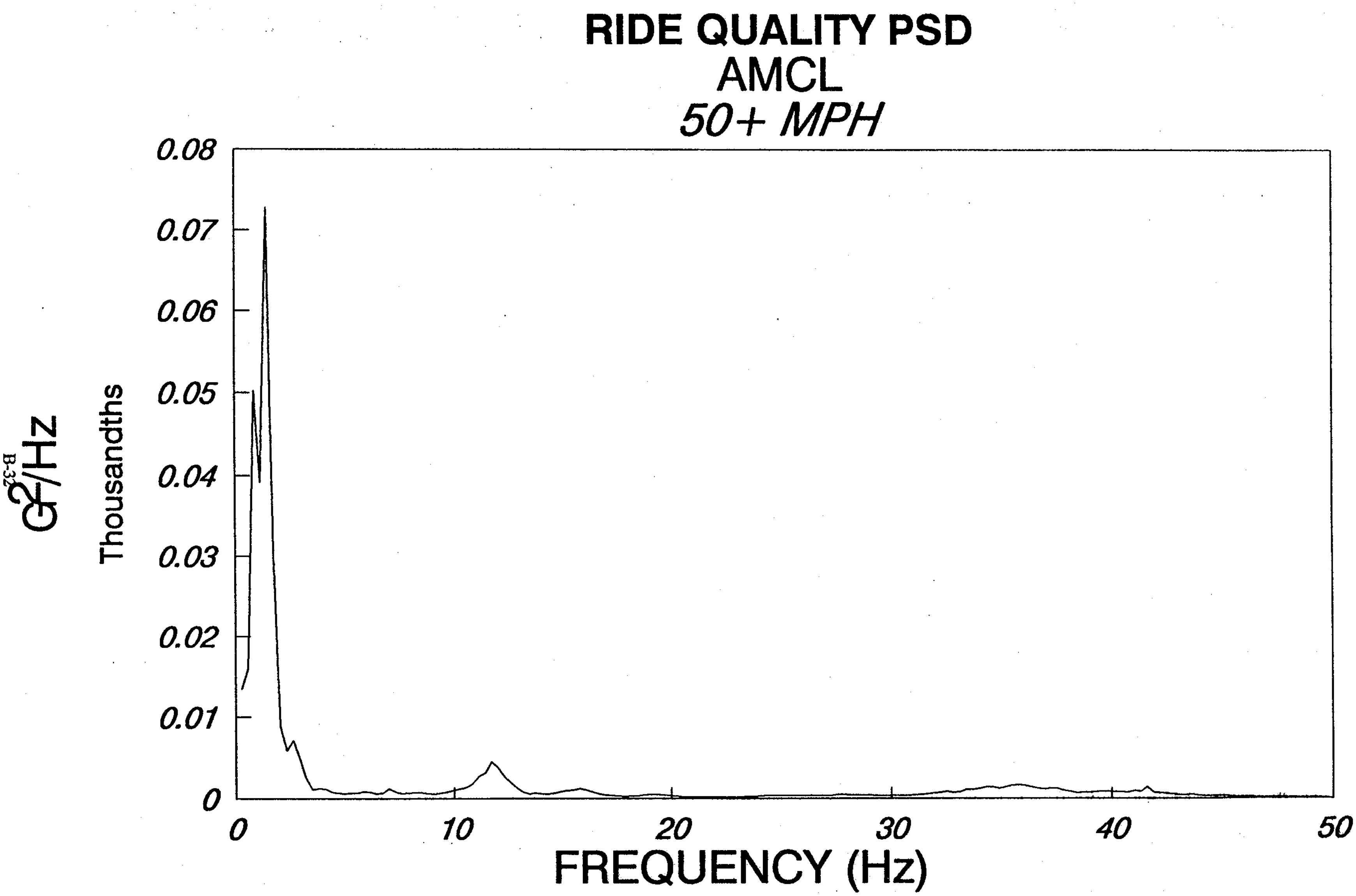
RMS = 0.108 G's
WEIGHT = 133,000 LBS.

RIDE QUALITY PSD
DMCL
40 - 49 MPH



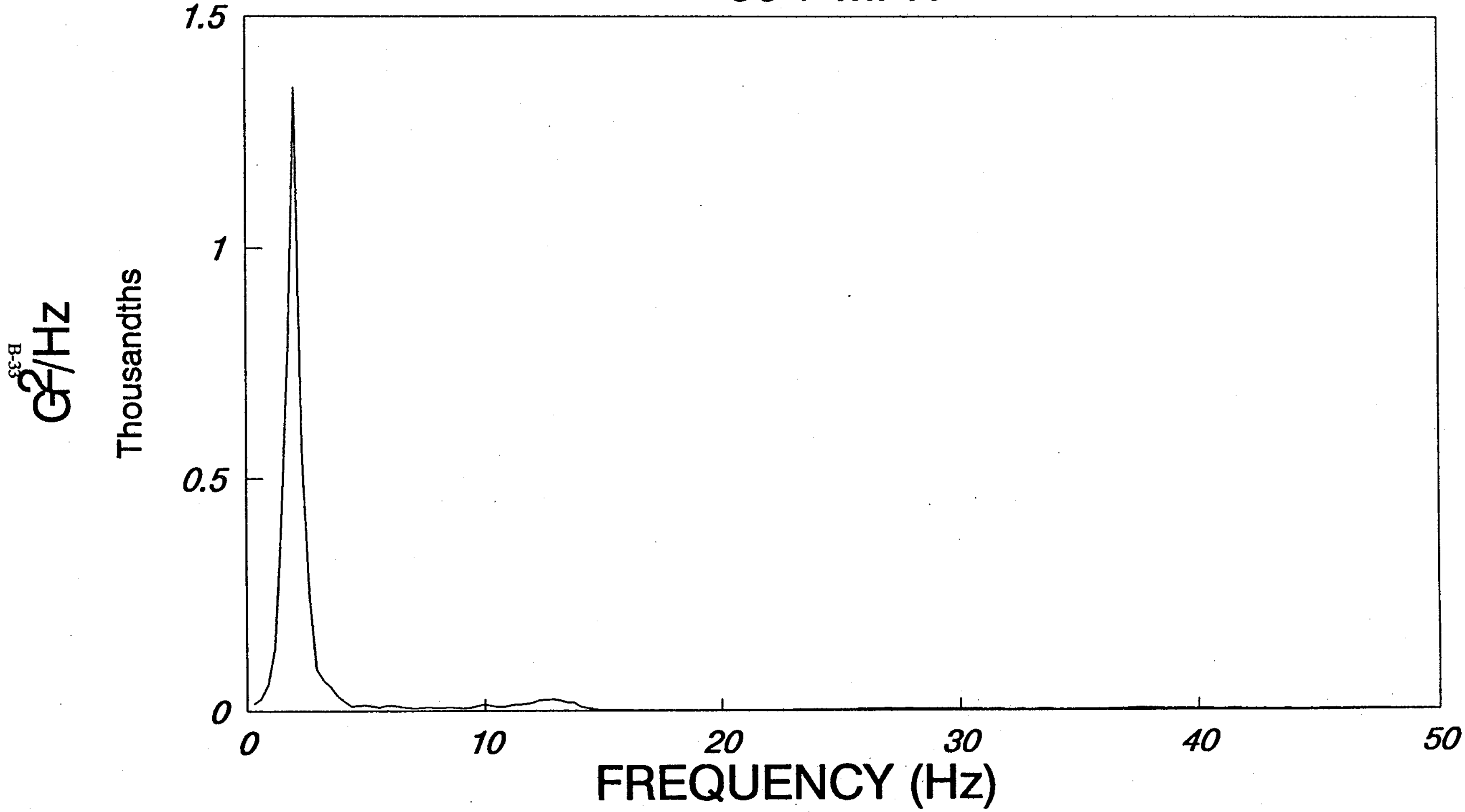
RMS = 0.030 G's
WEIGHT = 133,000 LBS.


RIDE QUALITY PSD
AMCV
50+ MPH
G²/Hz
Thousandths
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.029 G's
WEIGHT = 166,000 LBS.

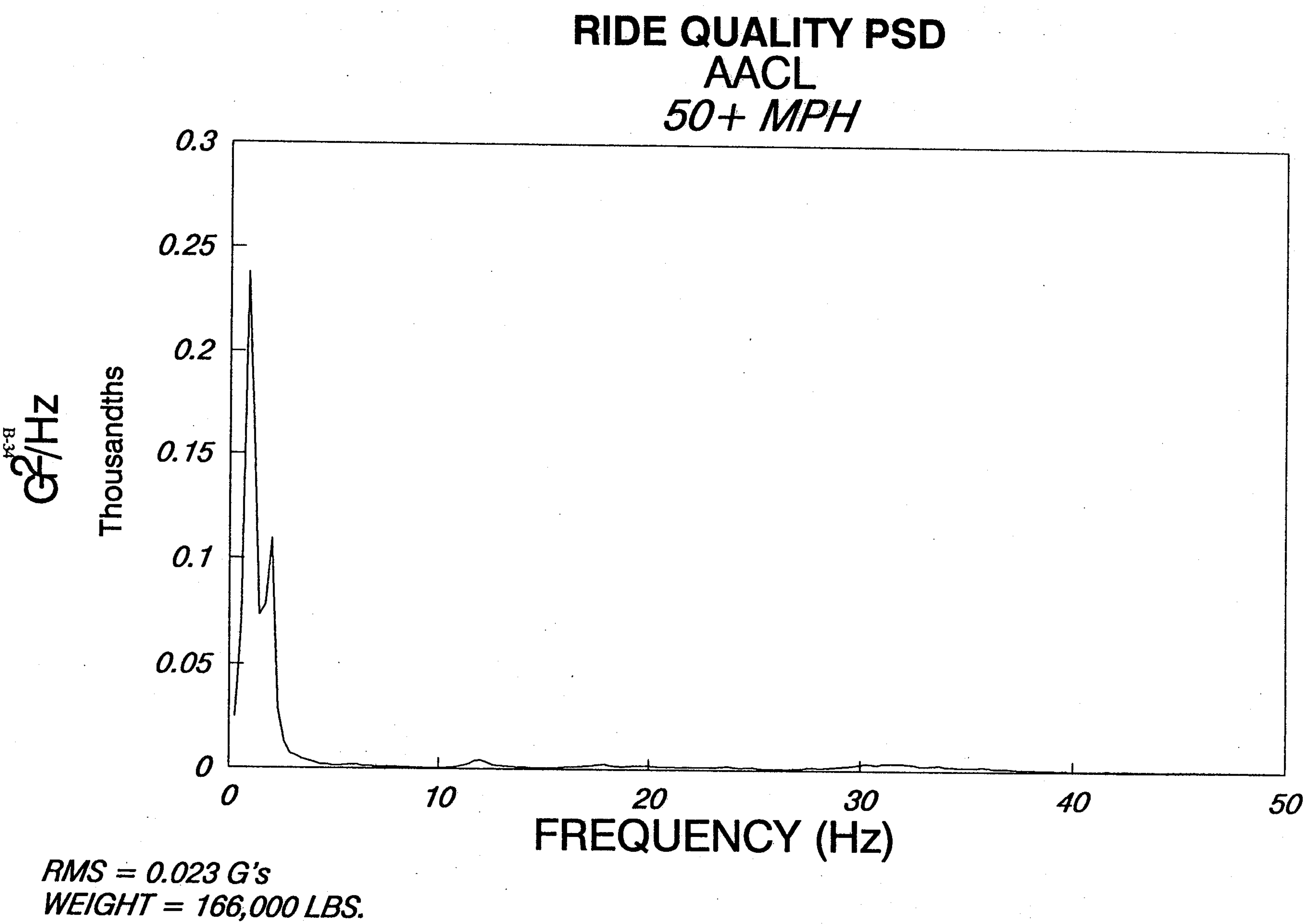


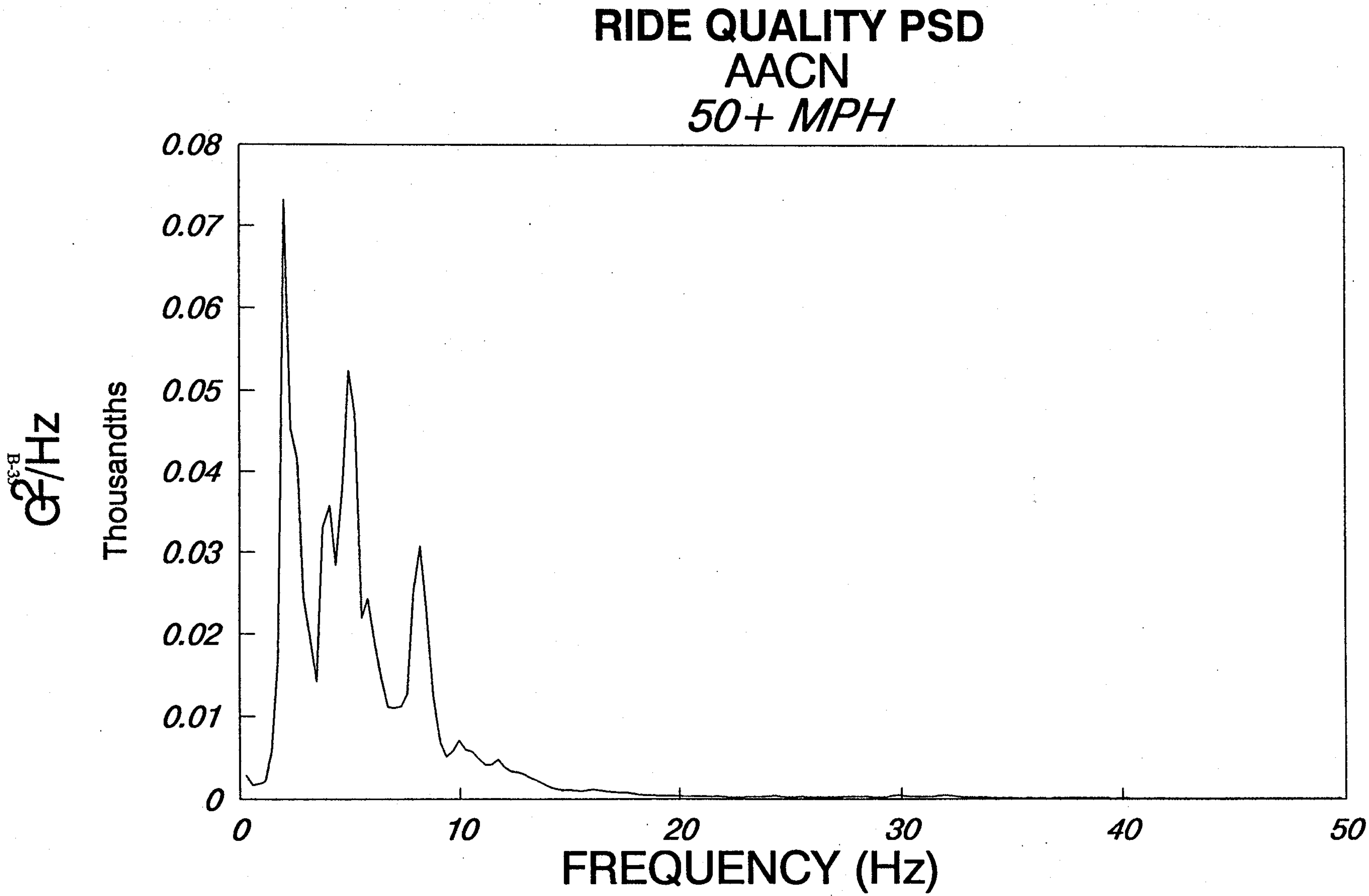
RMS = 0.017 G's
WEIGHT = 166,000 LBS.

RIDE QUALITY PSD
AACV
50+ MPH

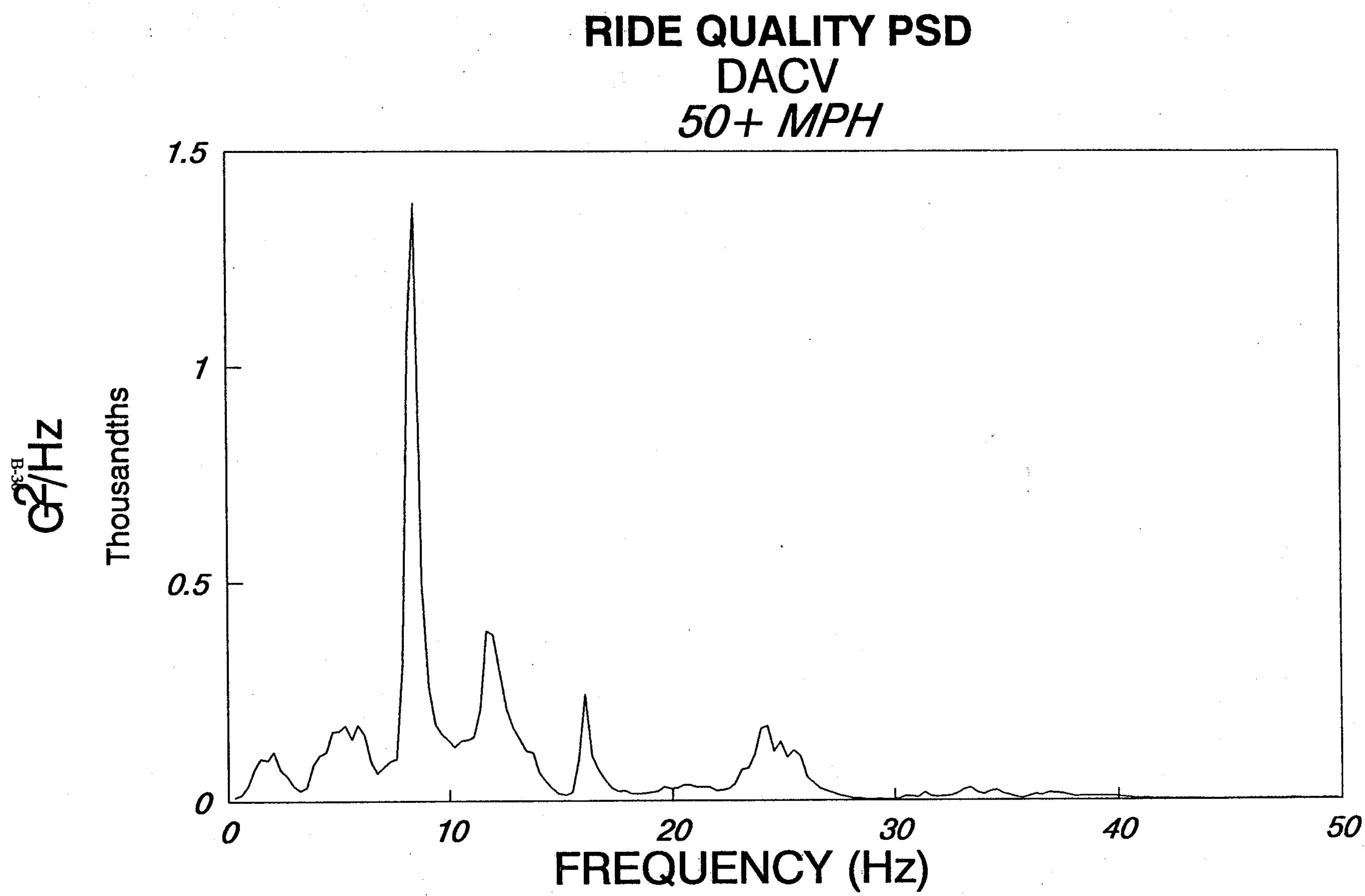


RMS = 0.038 G's
WEIGHT = 166,000 LBS.


RIDE QUALITY PSD
AACL
50+ MPH
G²/Hz
Thousandths
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
FREQUENCY (Hz)
RMS = 0.023 G's
WEIGHT = 166,000 LBS.

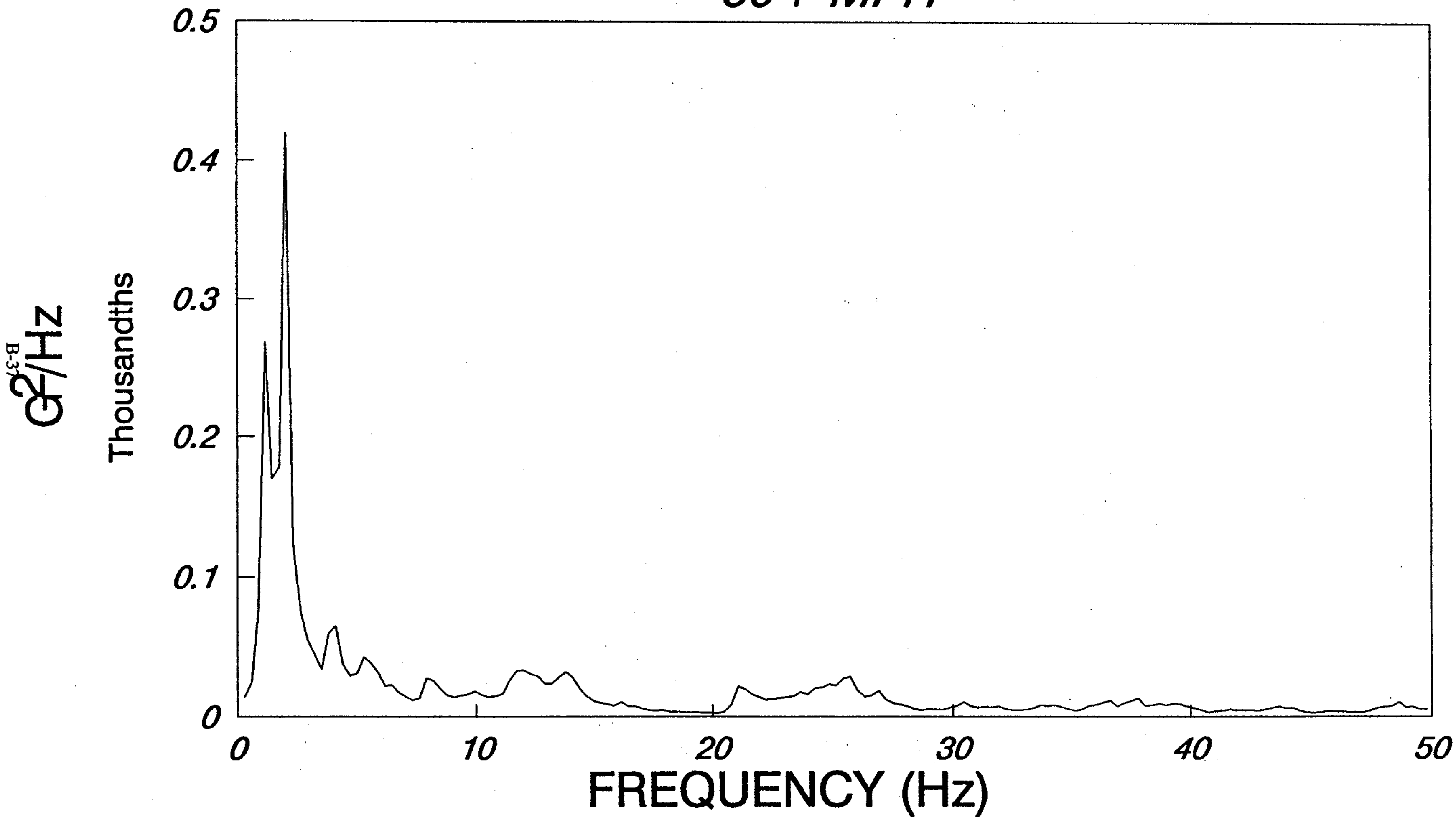


RMS = 0.018 G's
WEIGHT = 166,000 LBS.

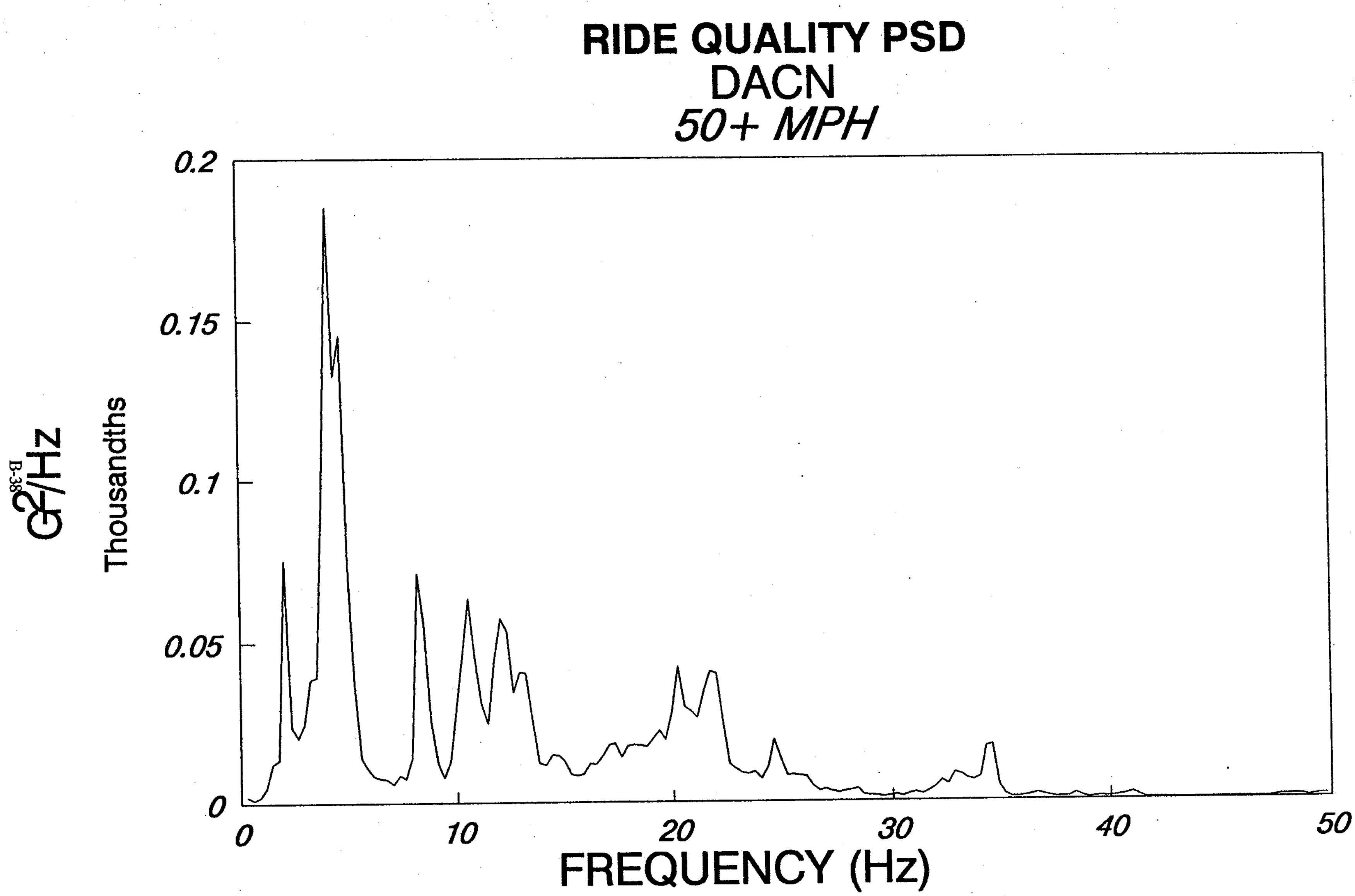


RMS = 0.062 G's
WEIGHT = 133,000 LBS.

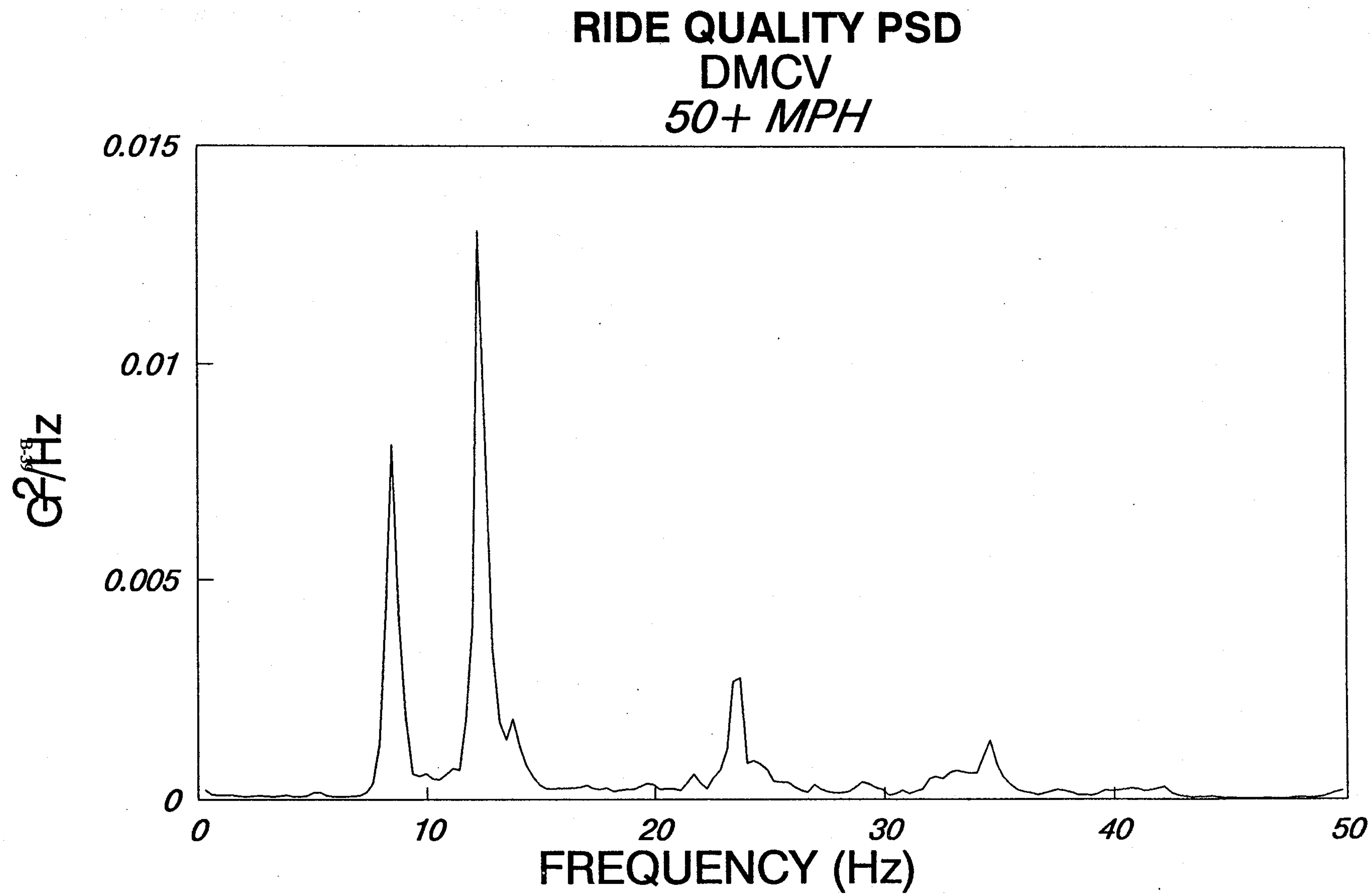
RIDE QUALITY PSD
DACL
50+ MPH



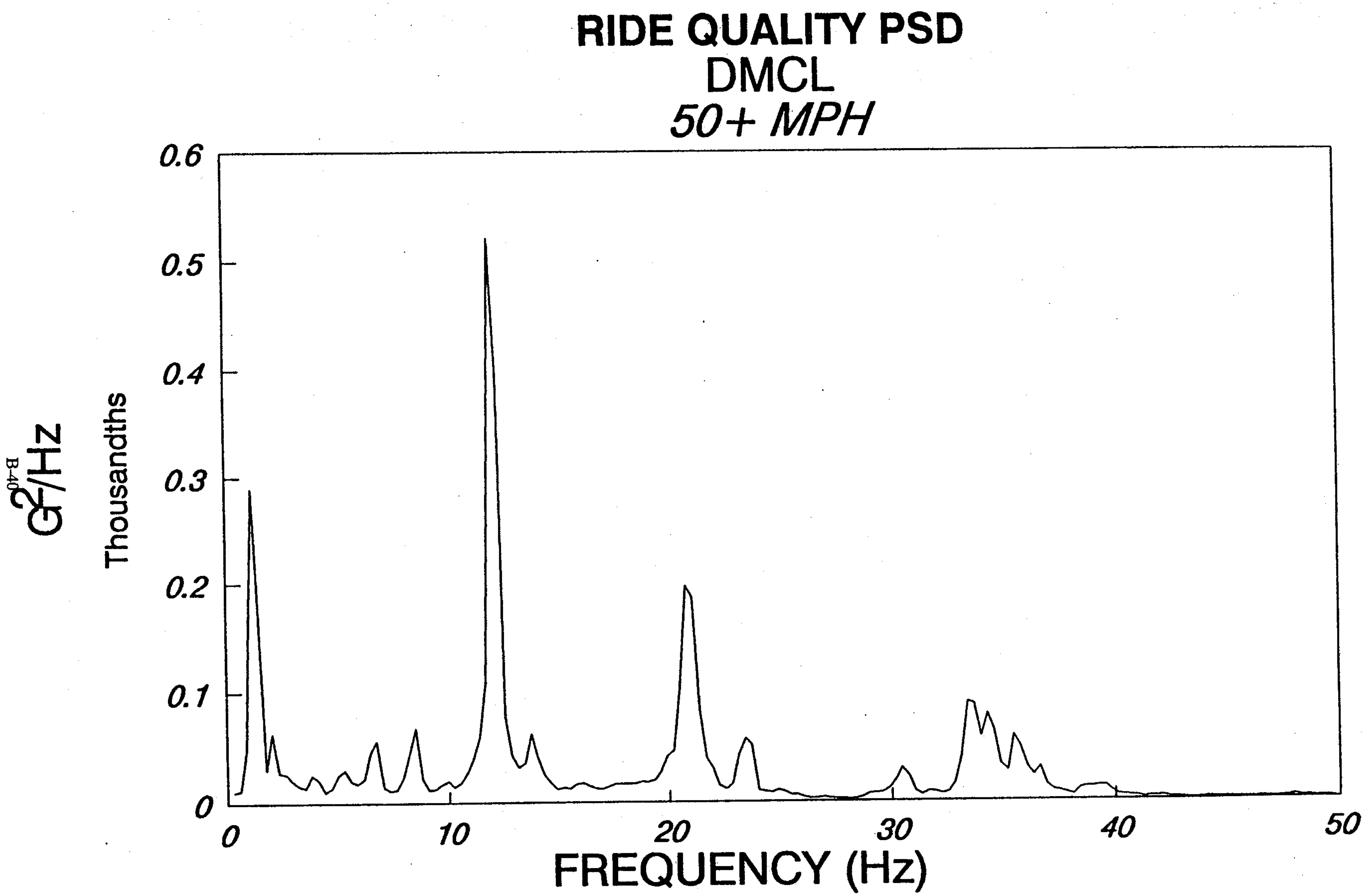
RMS = 0.037 G's
WEIGHT = 133,000 LBS.



RMS = 0.031 G's
WEIGHT = 133,000 LBS.



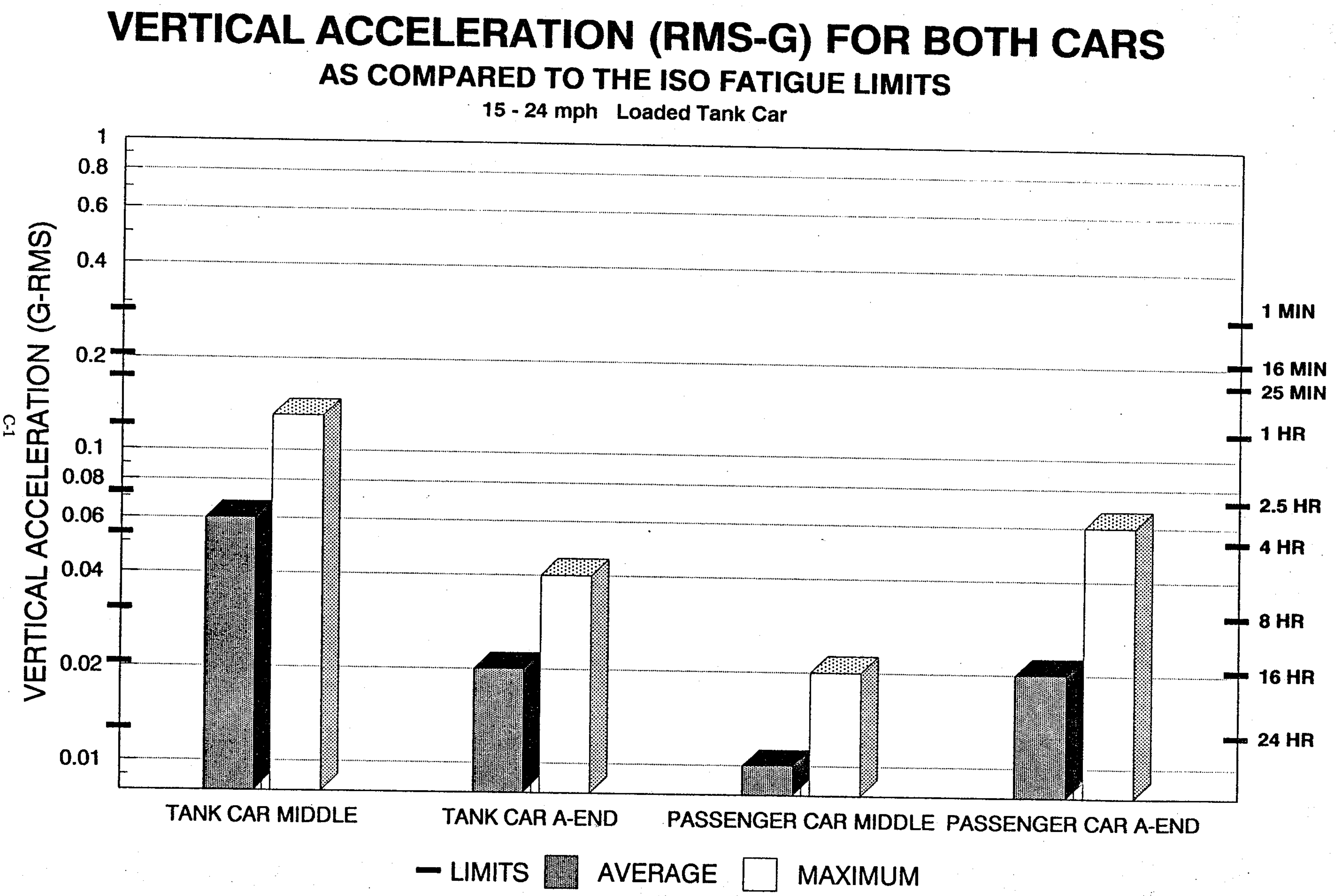
RMS = 0.183 G's
WEIGHT = 133,000 LBS.



RMS = 0.043 G's
WEIGHT = 133,000 LBS.

Appendix C

Tank Car and Passenger Car Vibration Levels



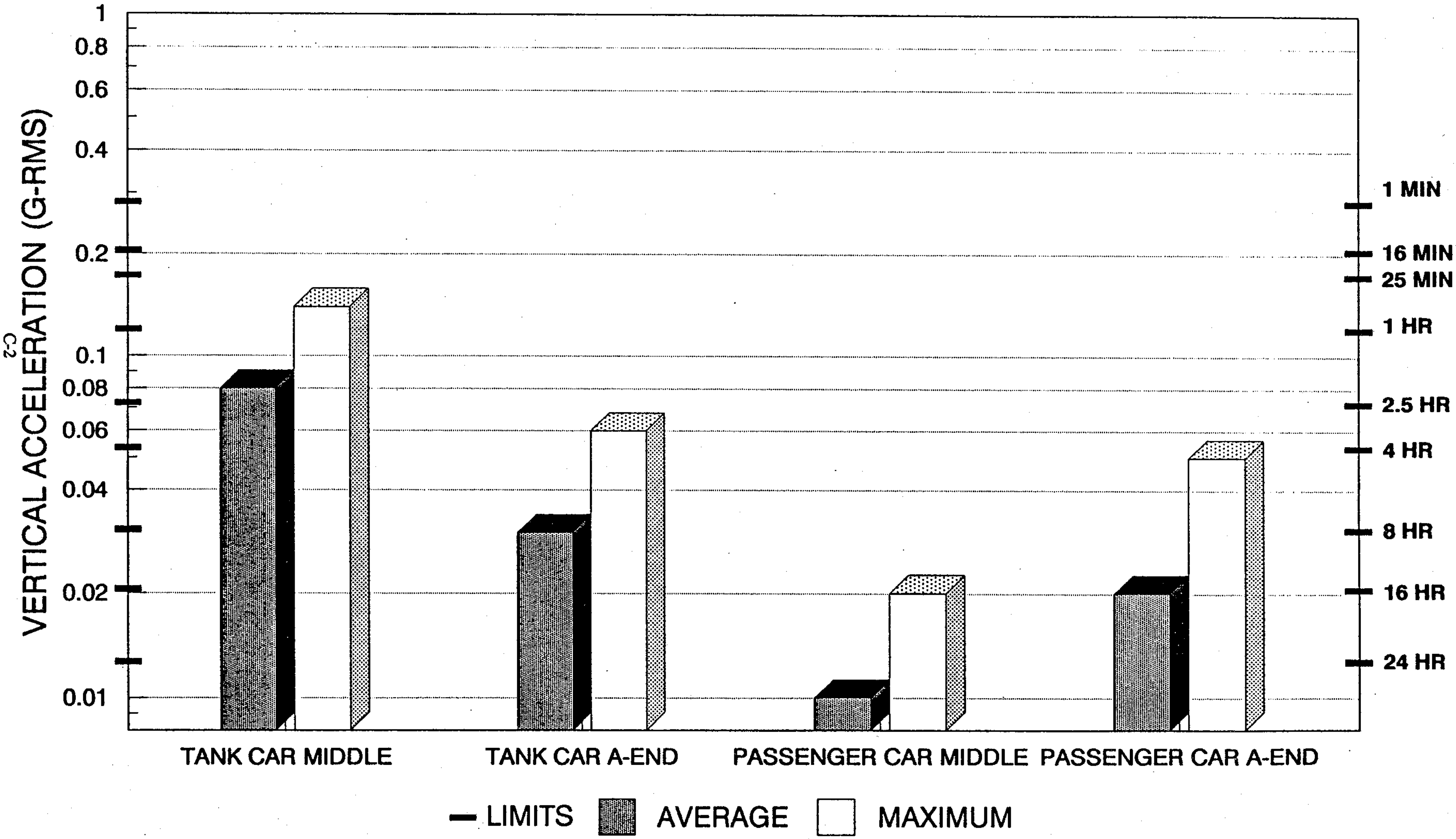
VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
15 - 24 mph Loaded Tank Car
VERTICAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR MIDDLE
TANK CAR A-END
PASSENGER CAR MIDDLE
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

C-1

VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

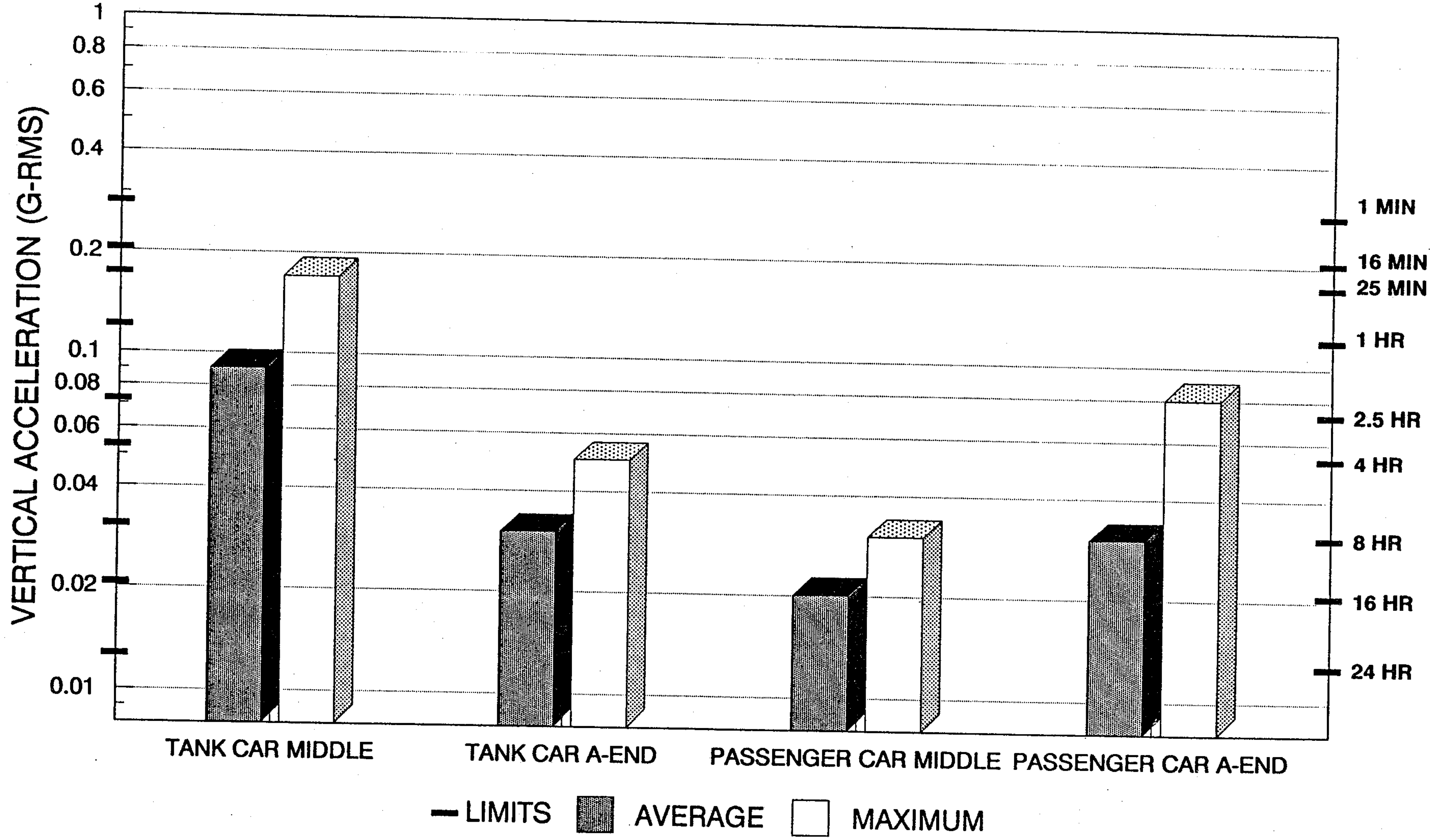
25 - 39 mph Loaded Tank Car



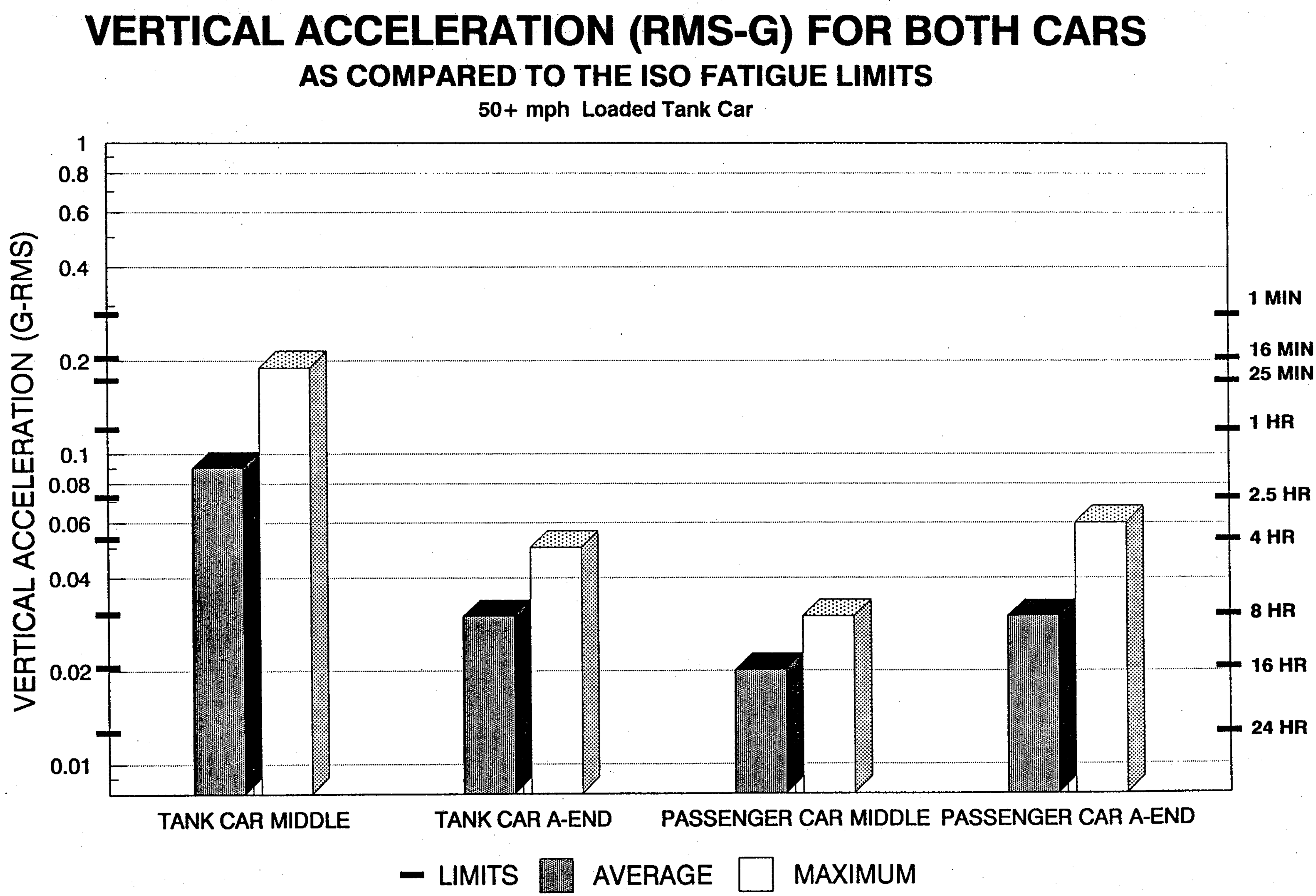
VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

40 - 49 mph Loaded Tank Car



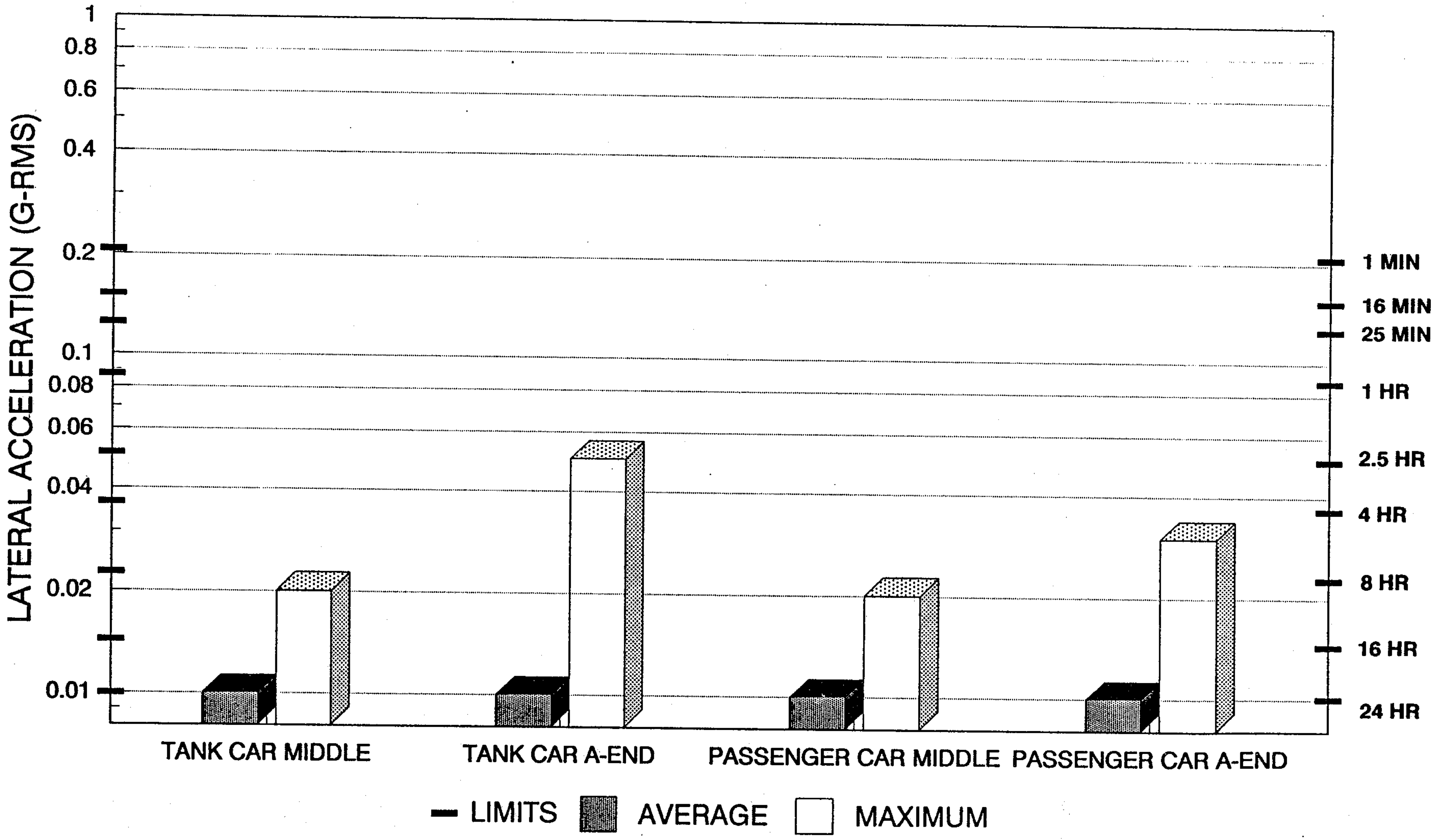
C-3


VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
50+ mph Loaded Tank Car
VERTICAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR MIDDLE
TANK CAR A-END
PASSENGER CAR MIDDLE
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

LATERAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

25 - 39 mph Loaded Tank Car

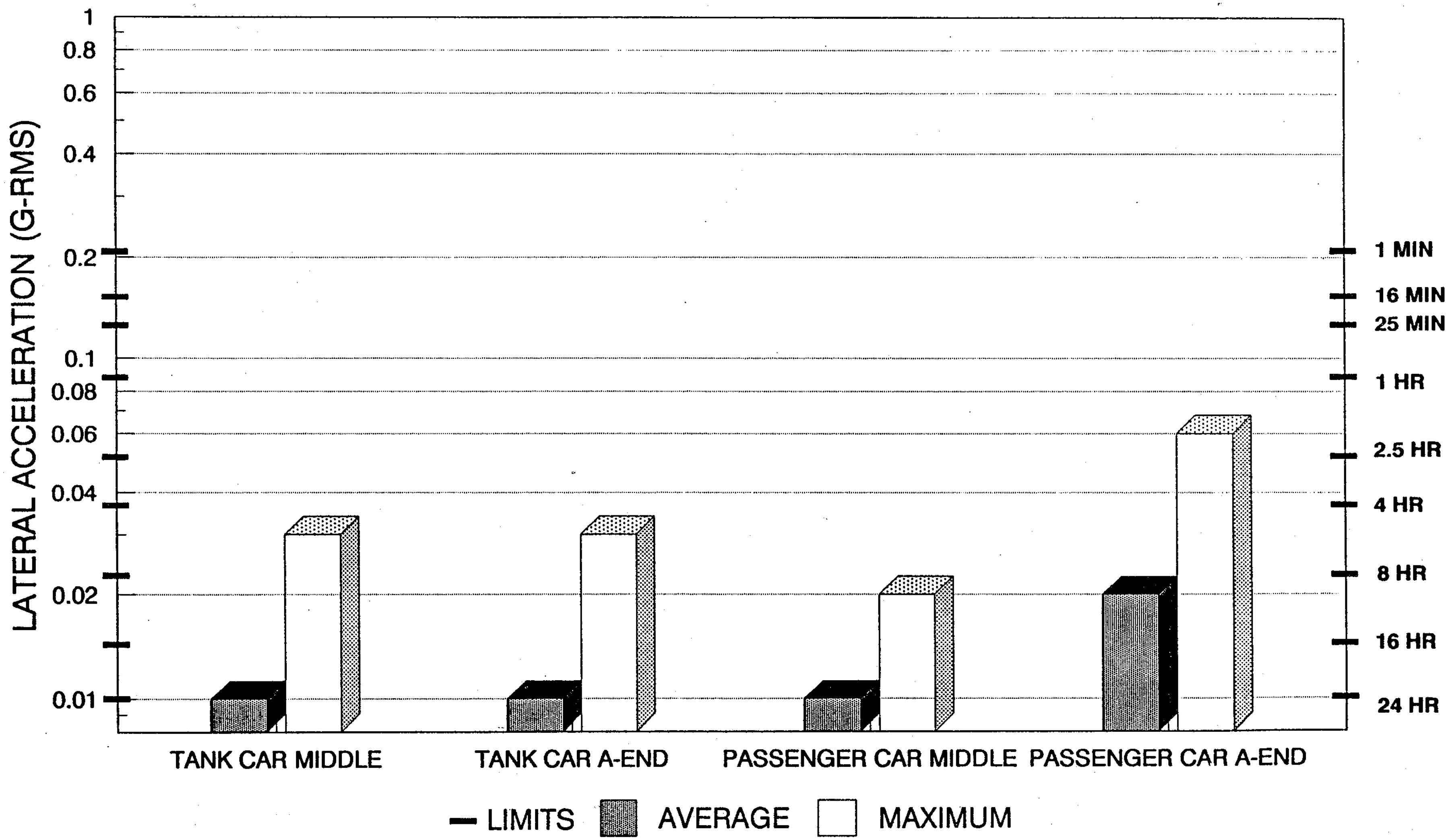


C-5

LATERAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

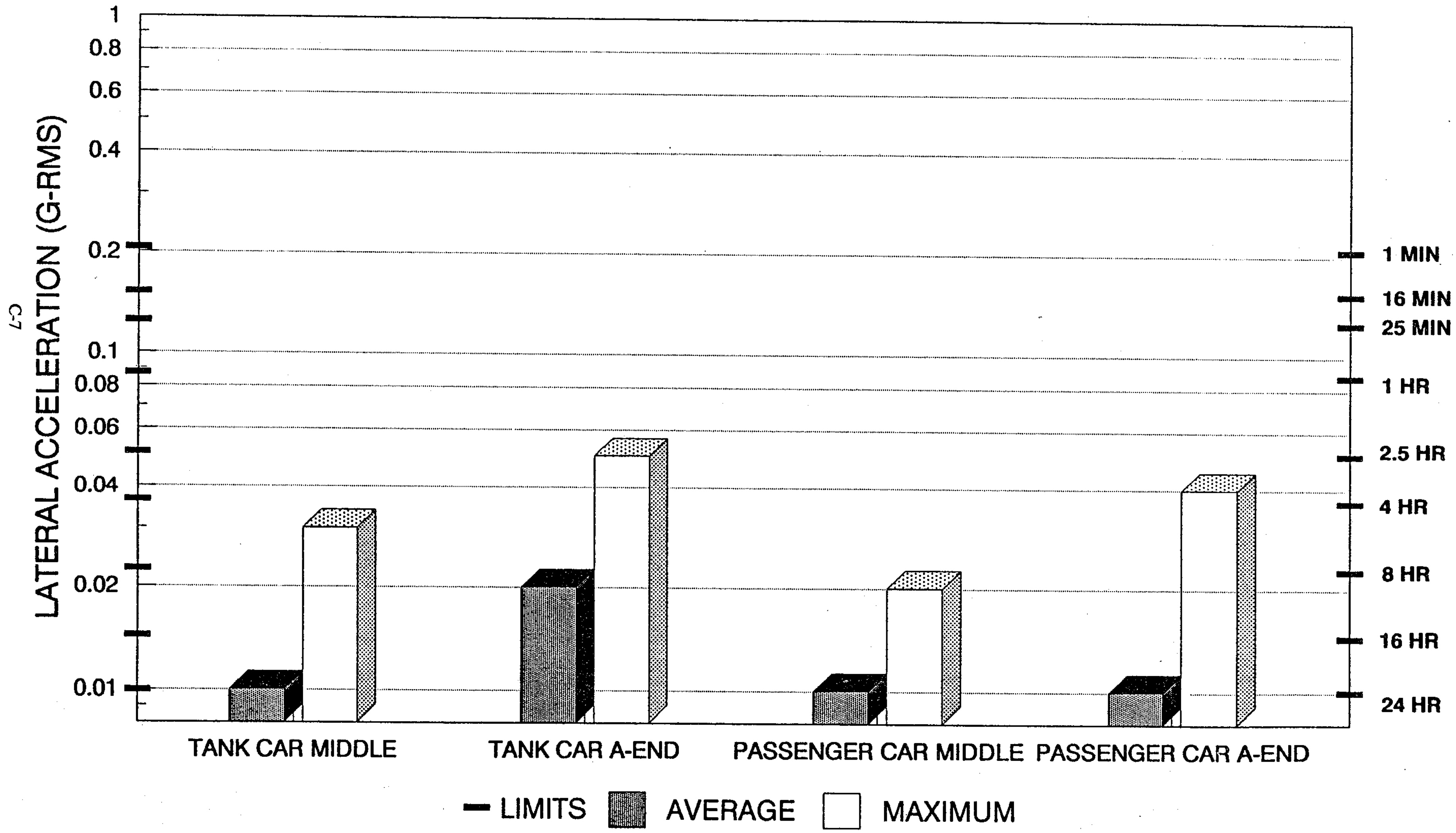
15 - 24 mph Loaded Tank Car



LATERAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

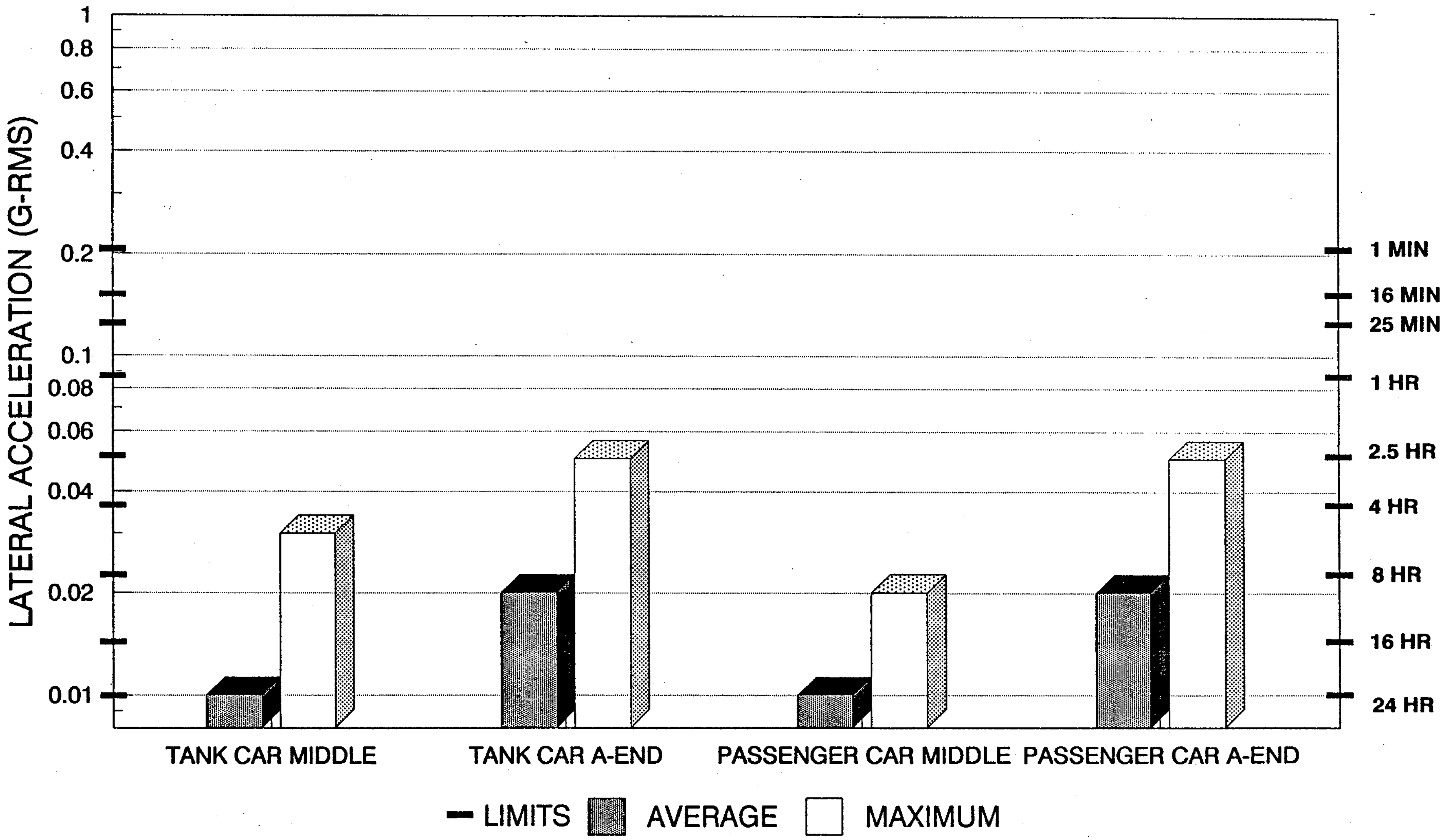
40 - 49 mph Loaded Tank Car



LATERAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

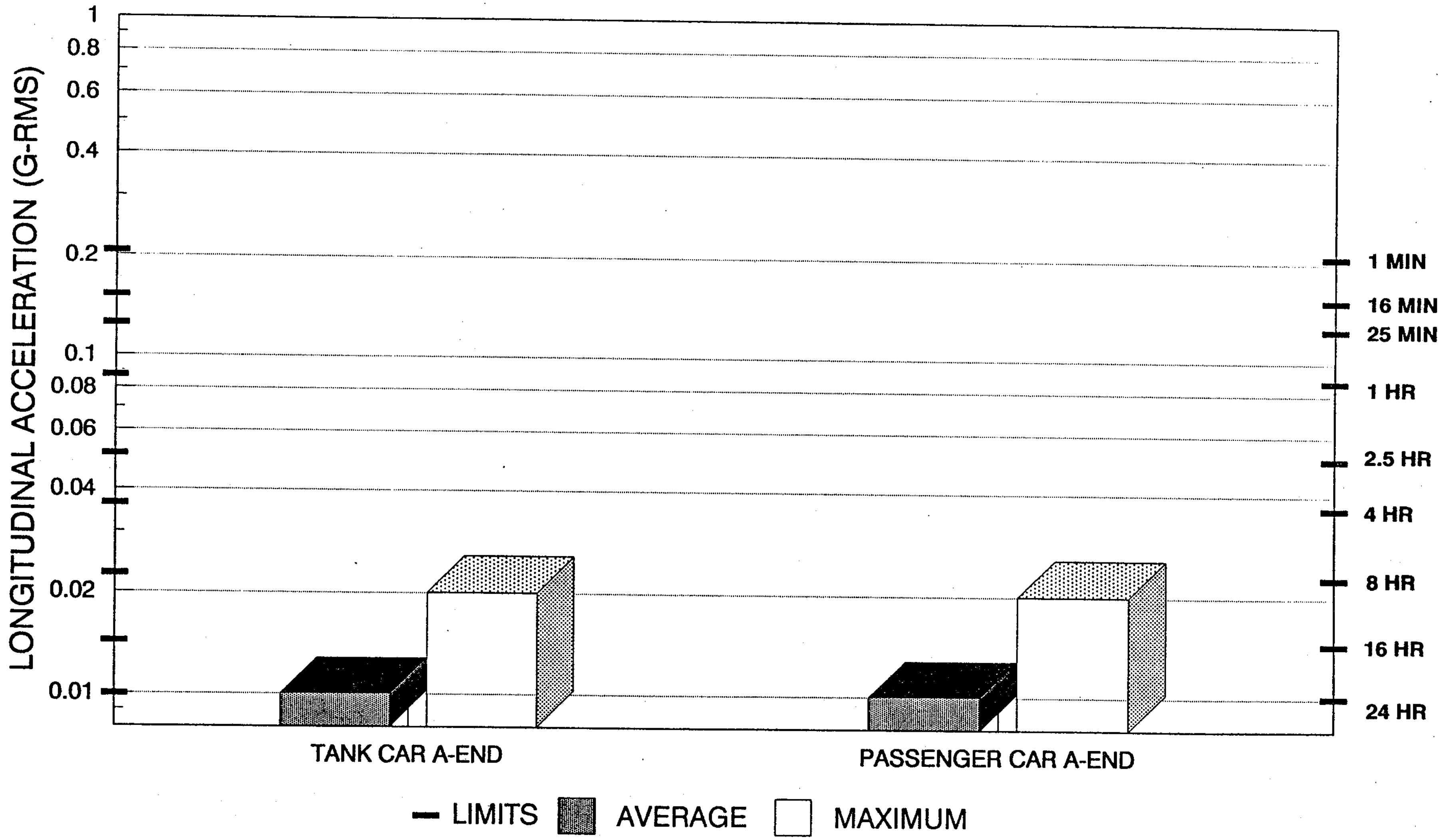
50+ mph Loaded Tank Car

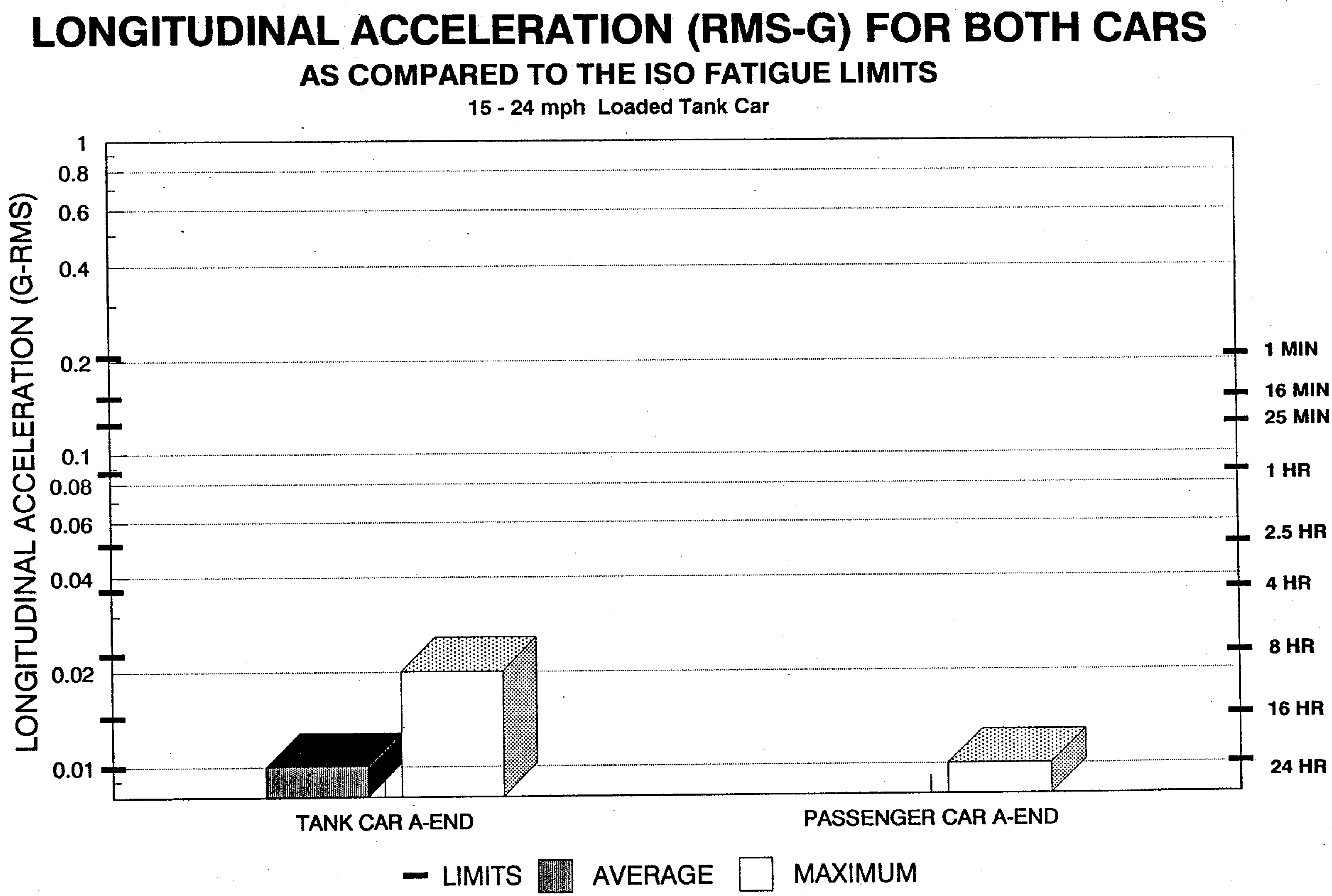


LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS

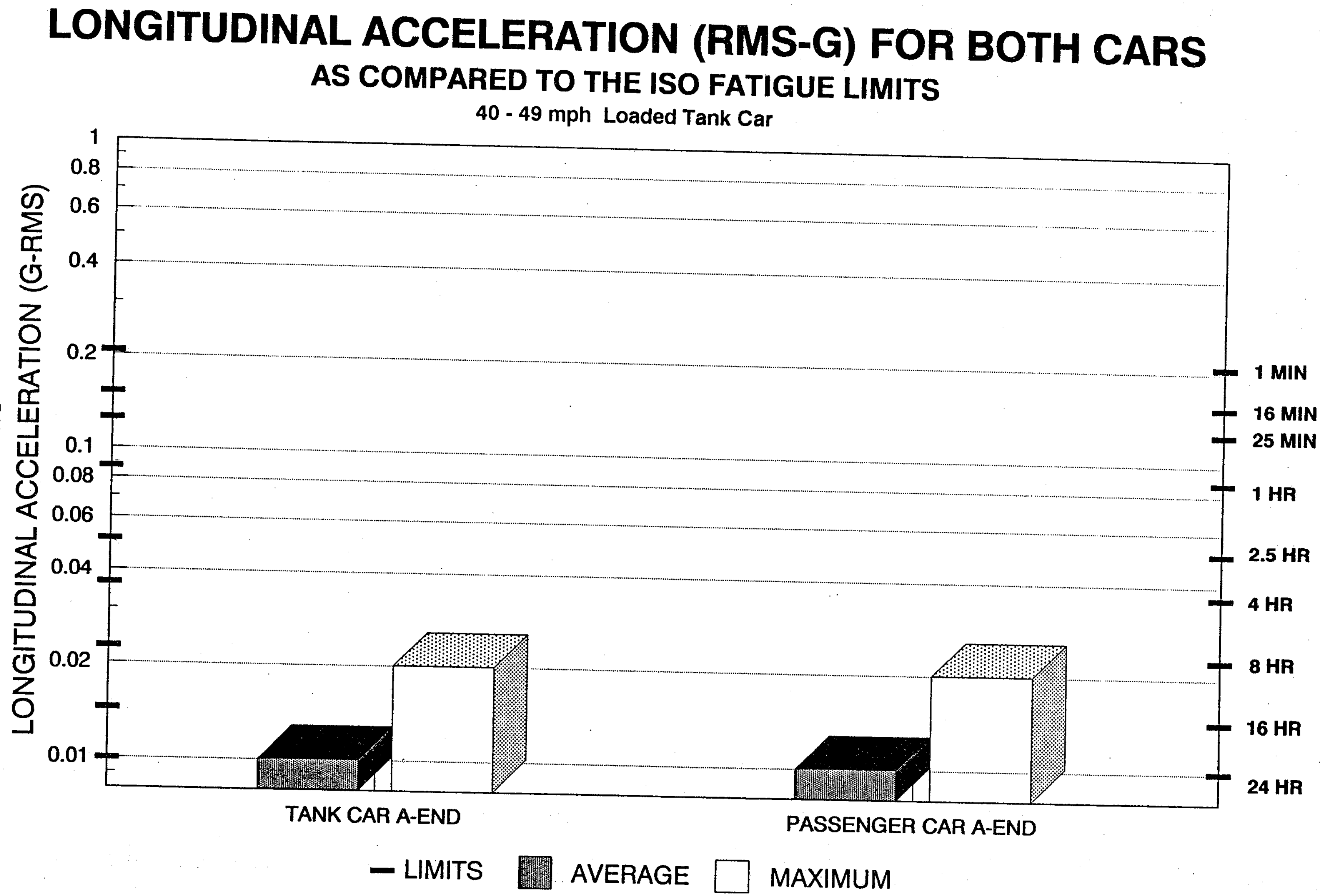
AS COMPARED TO THE ISO FATIGUE LIMITS

25 - 39 mph Loaded Tank Car

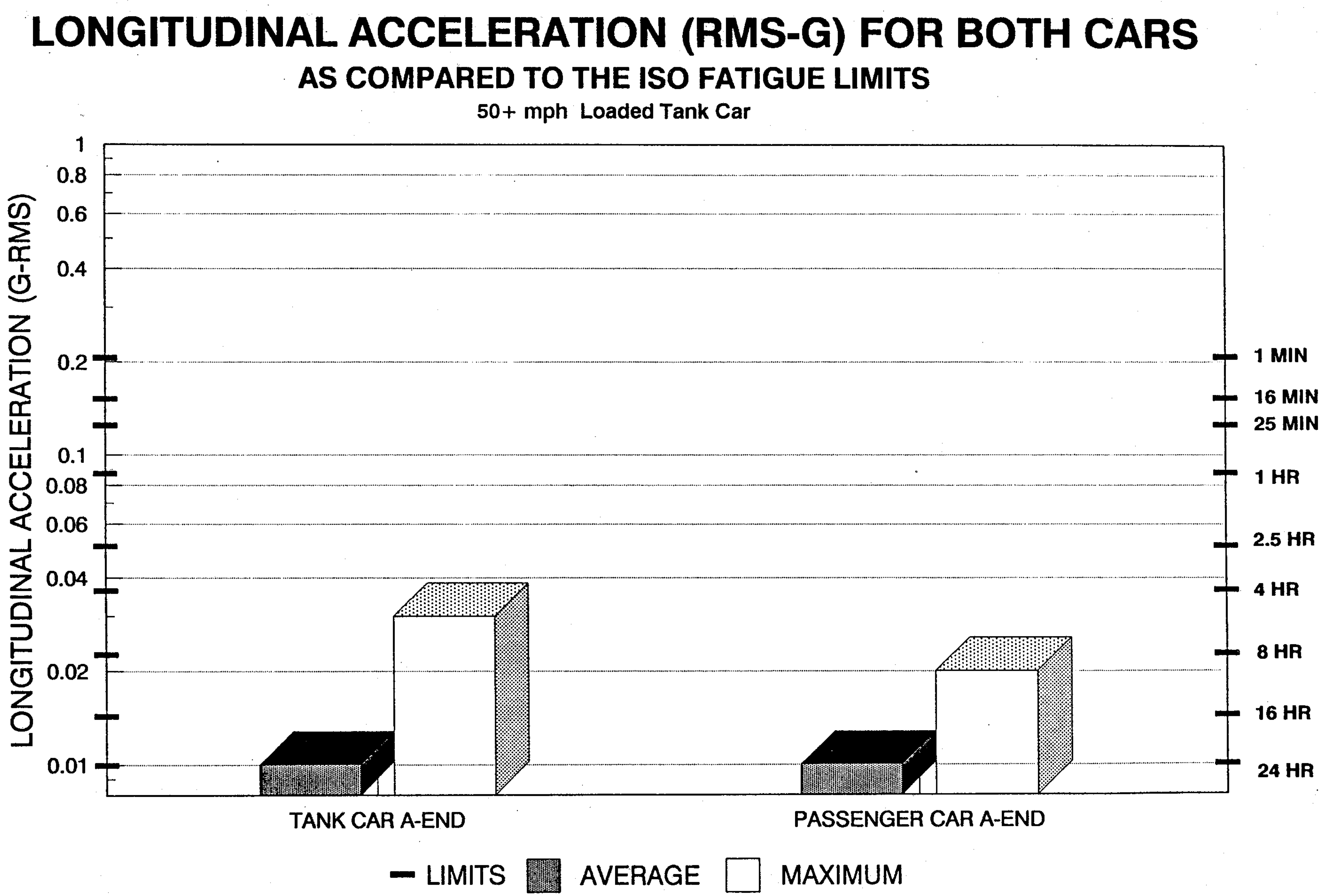



LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
15 - 24 mph Loaded Tank Car
LONGITUDINAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR A-END
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

C-10


LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
40 - 49 mph Loaded Tank Car
LONGITUDINAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR A-END
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

C-11

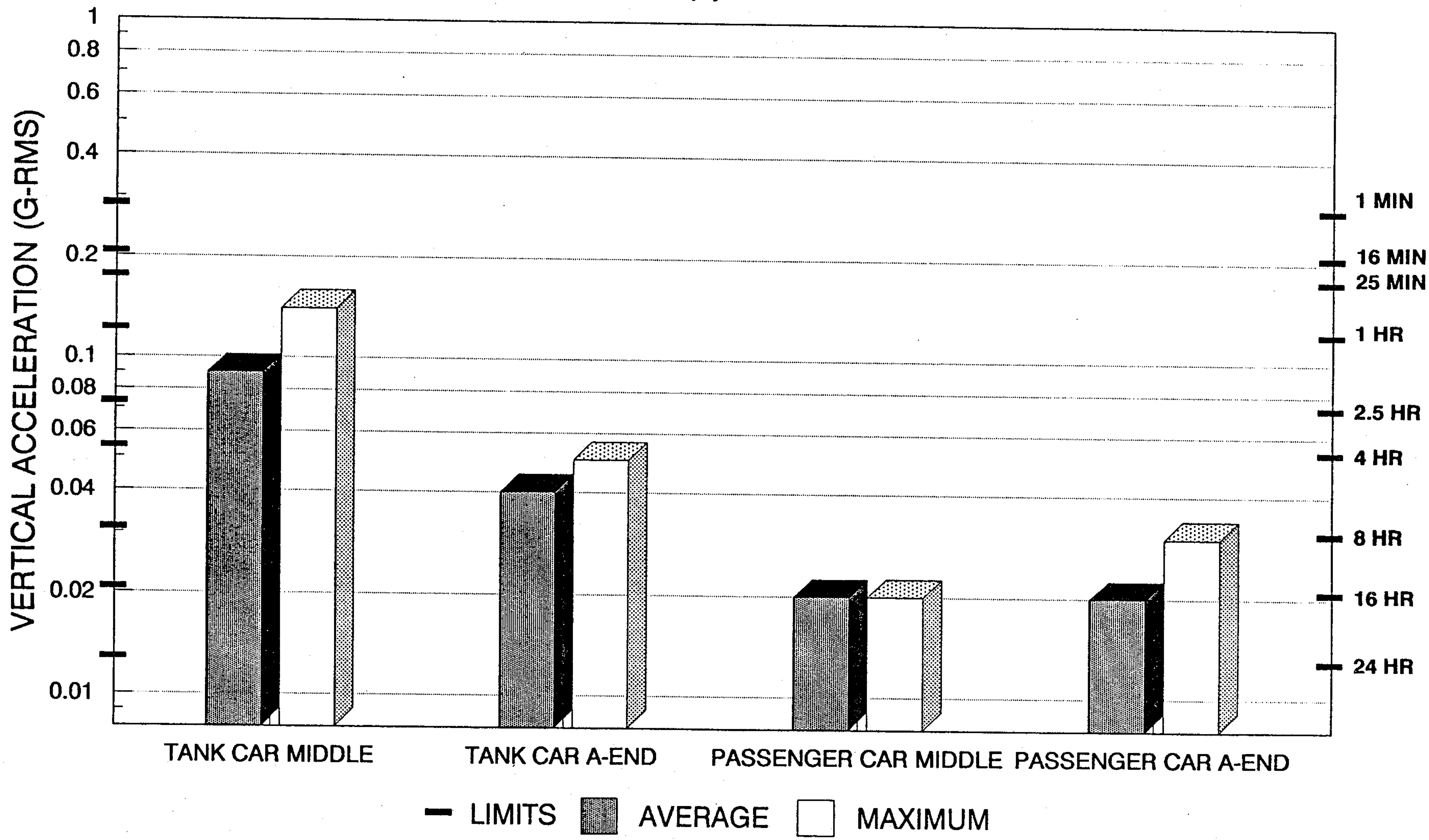


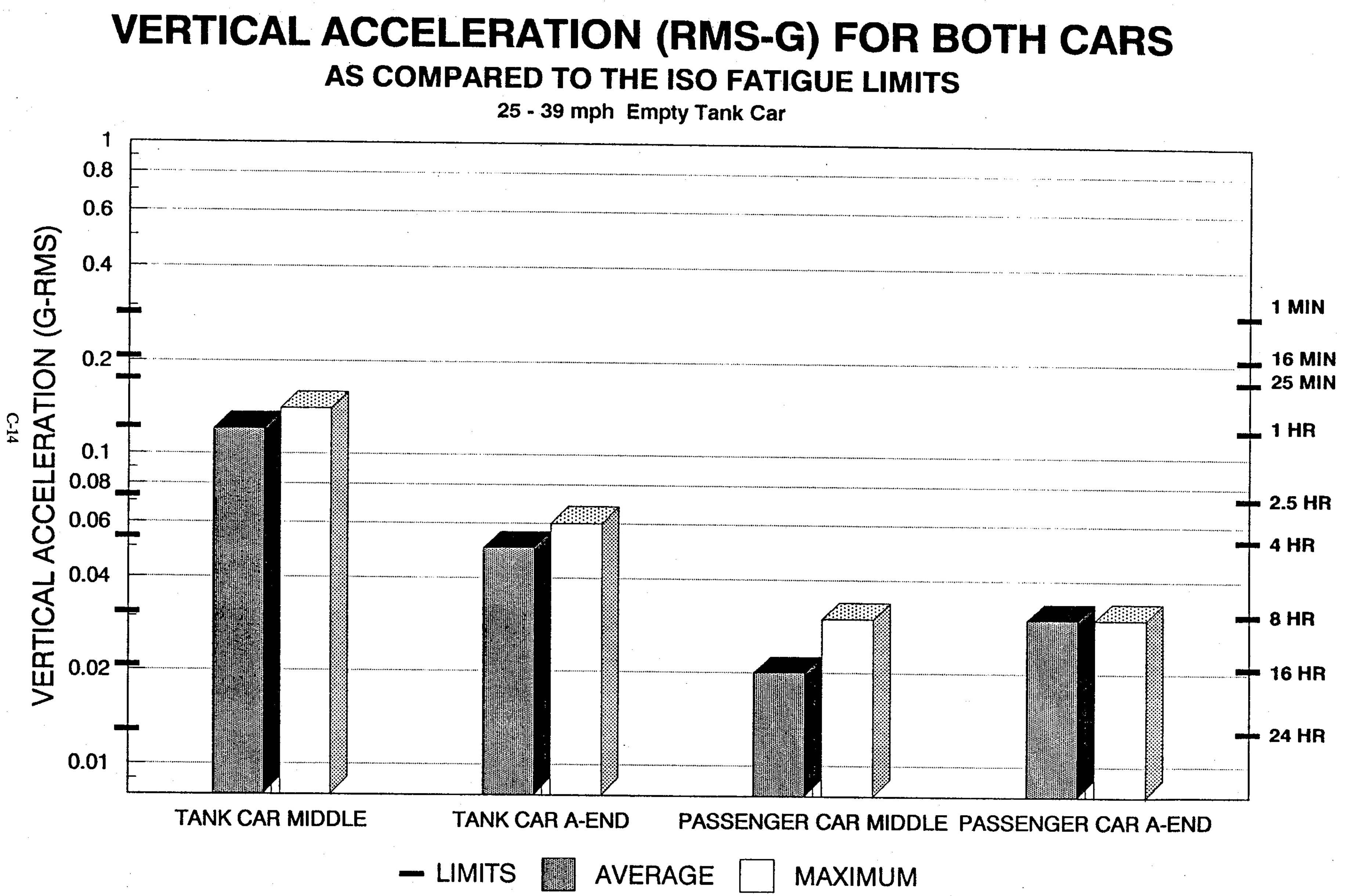
LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
50+ mph Loaded Tank Car
LONGITUDINAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR A-END
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

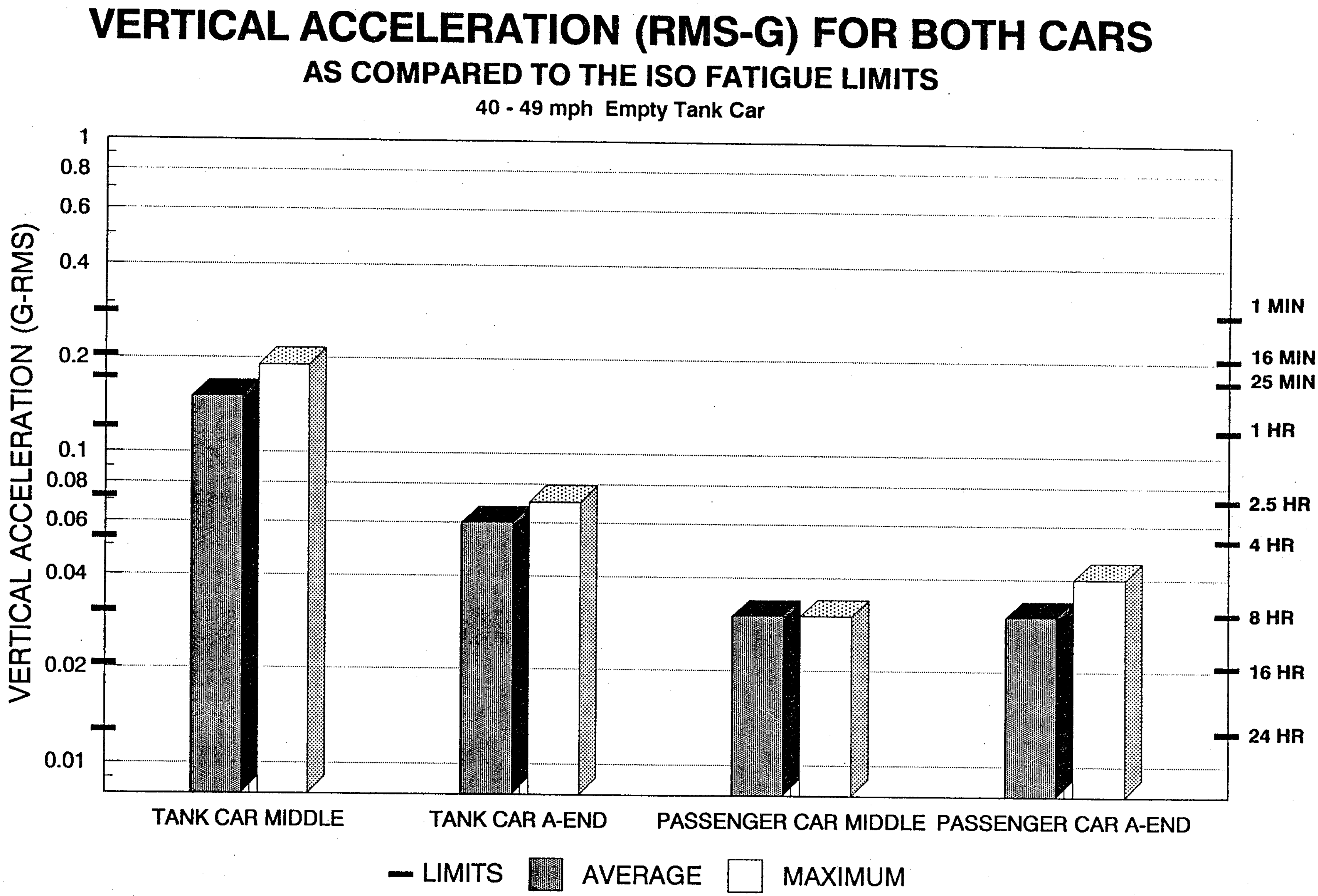
VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

15 - 24 mph Empty Tank Car



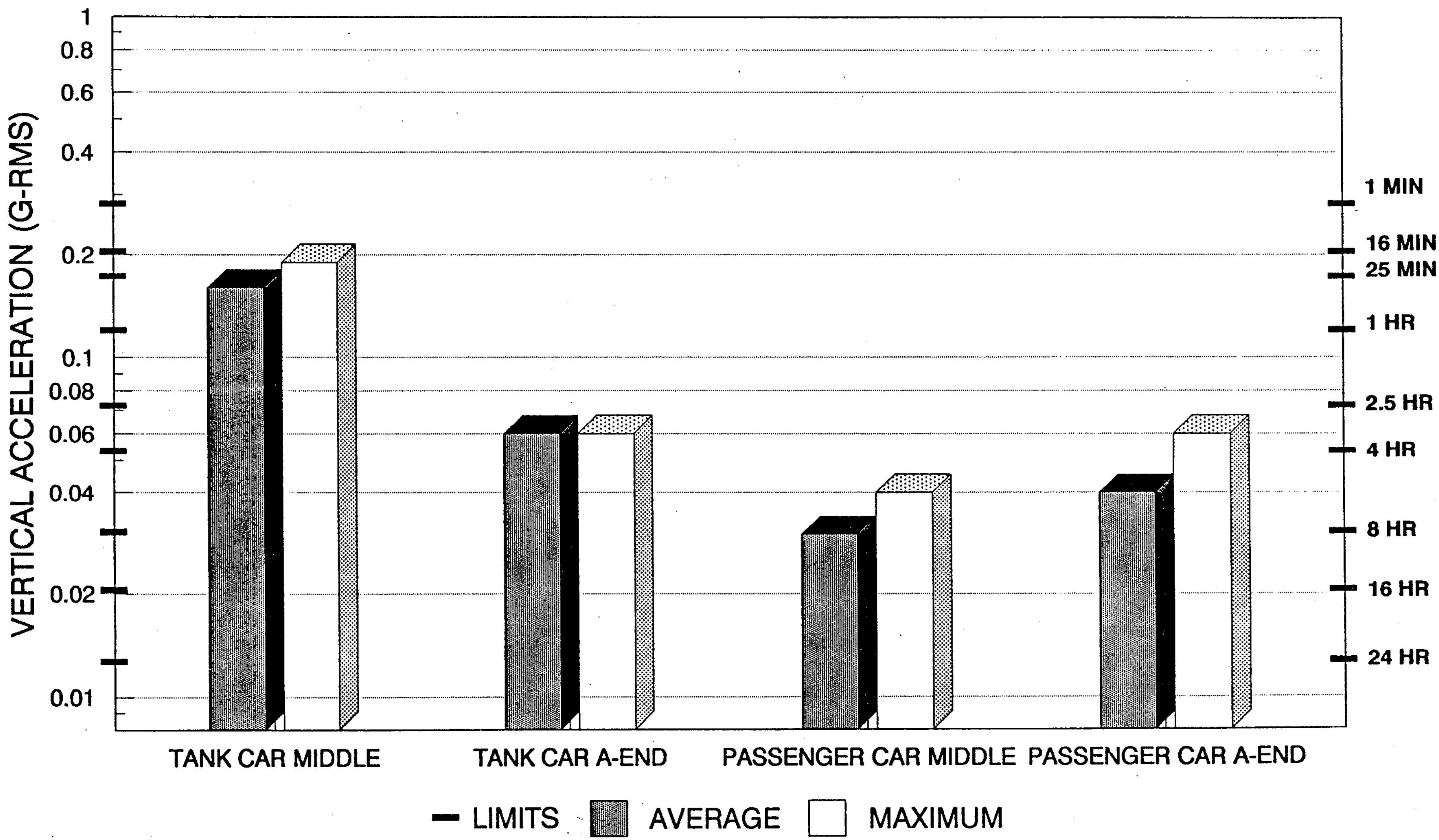

VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
25 - 39 mph Empty Tank Car
VERTICAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR MIDDLE
TANK CAR A-END
PASSENGER CAR MIDDLE
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM


VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
40 - 49 mph Empty Tank Car
VERTICAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR MIDDLE
TANK CAR A-END
PASSENGER CAR MIDDLE
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

VERTICAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

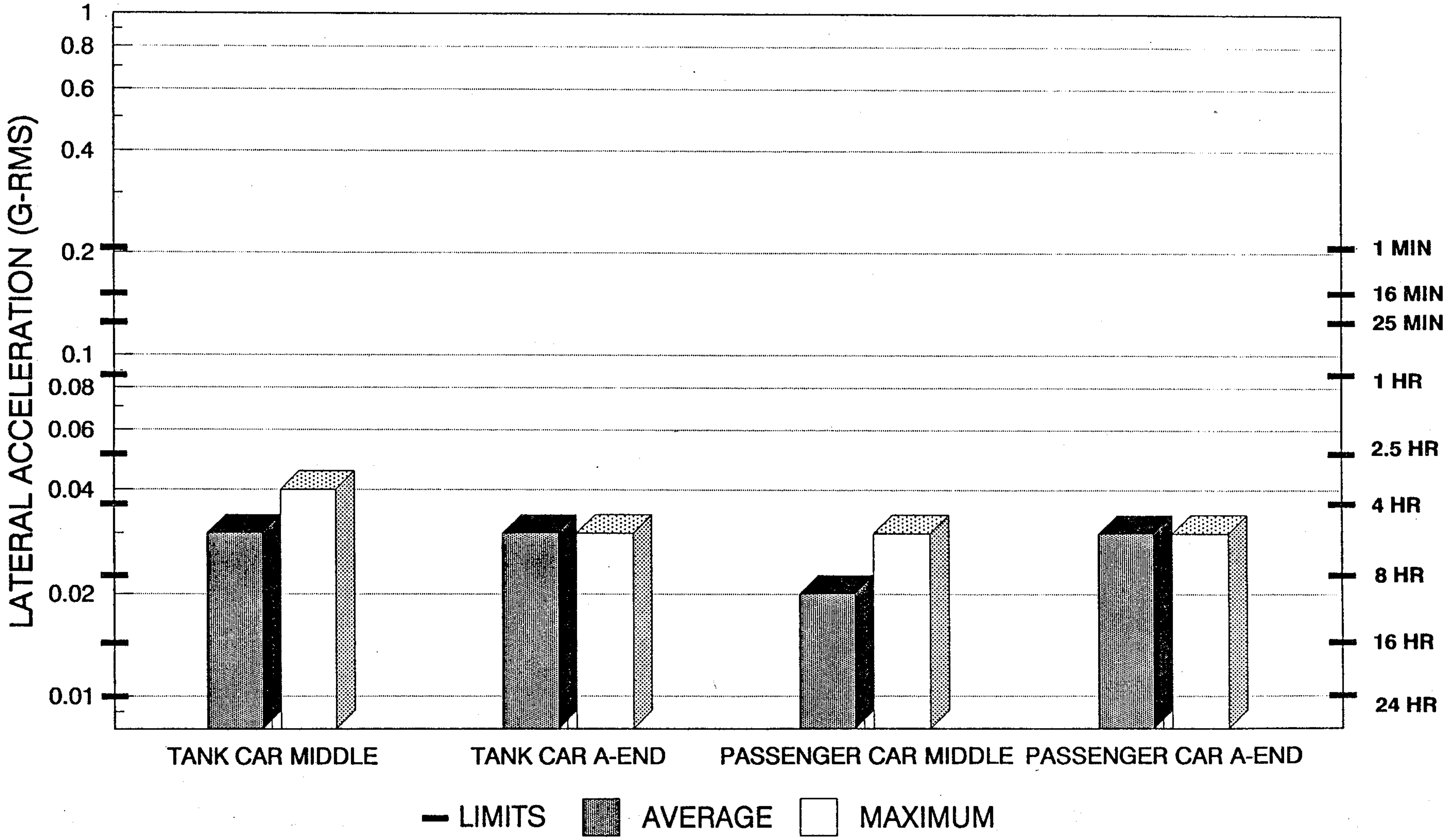
50+ mph Empty Tank Car



LATERAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

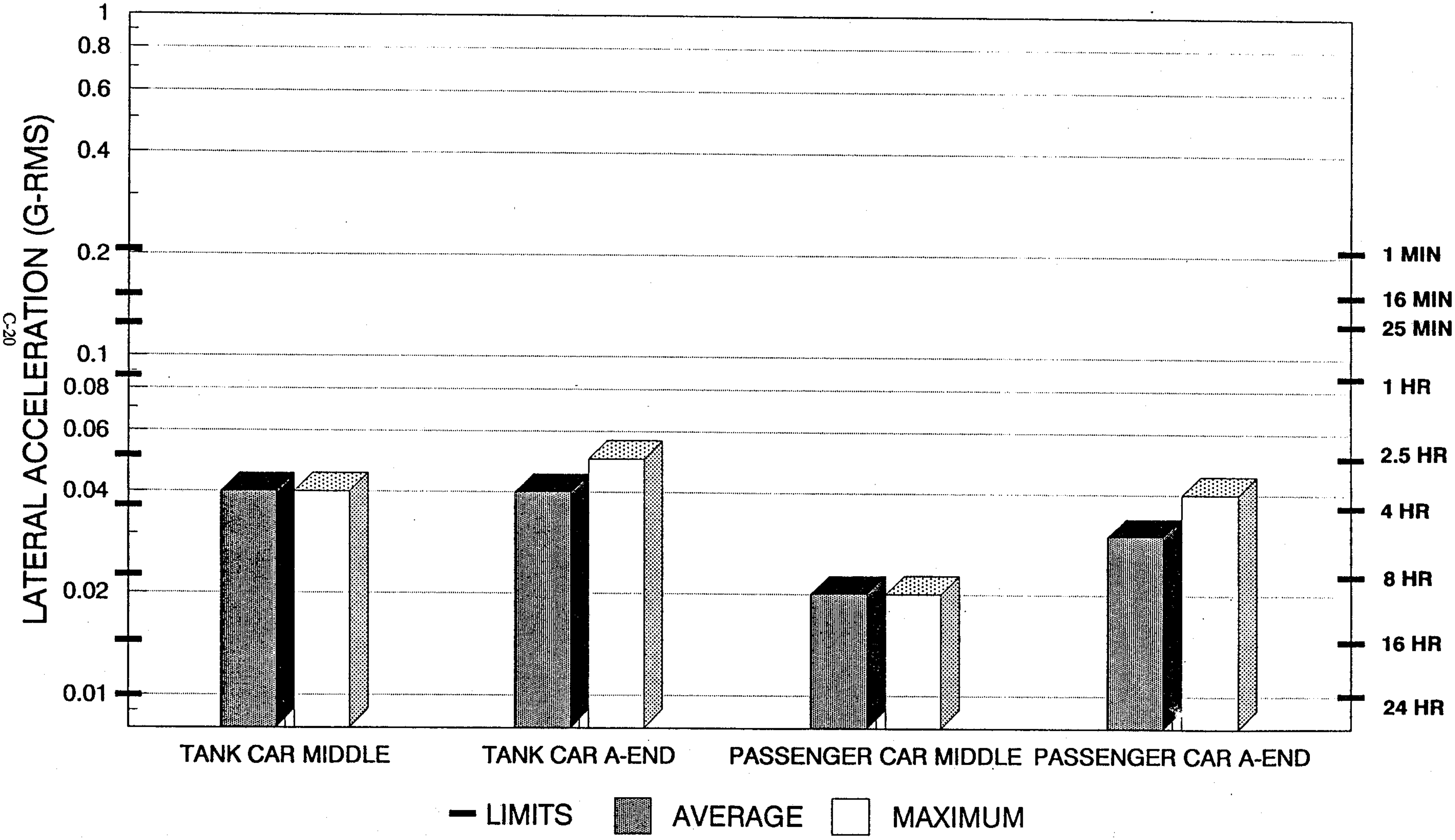
15 - 24 mph Empty Tank Car

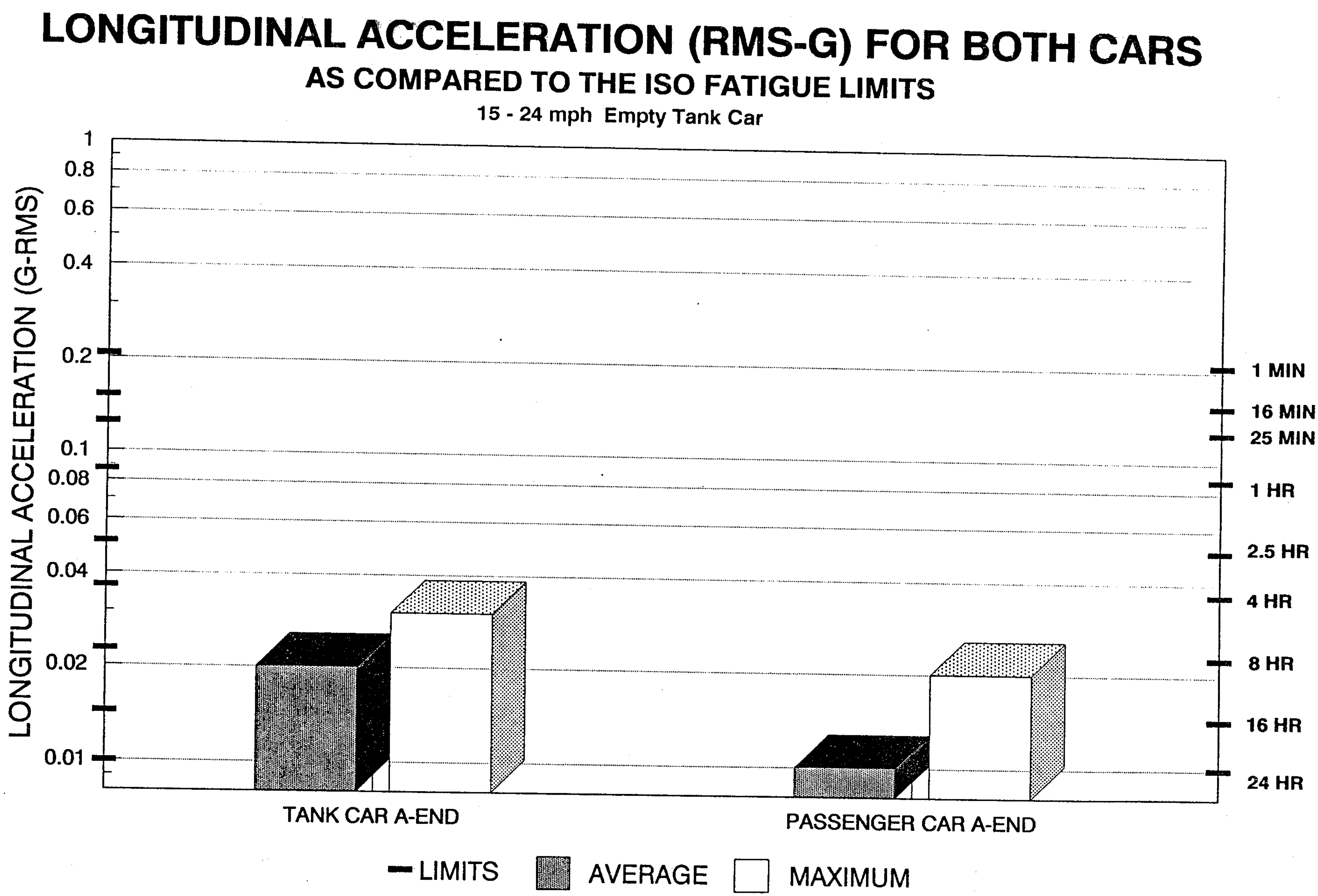


LATERAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

50+ mph Empty Tank Car

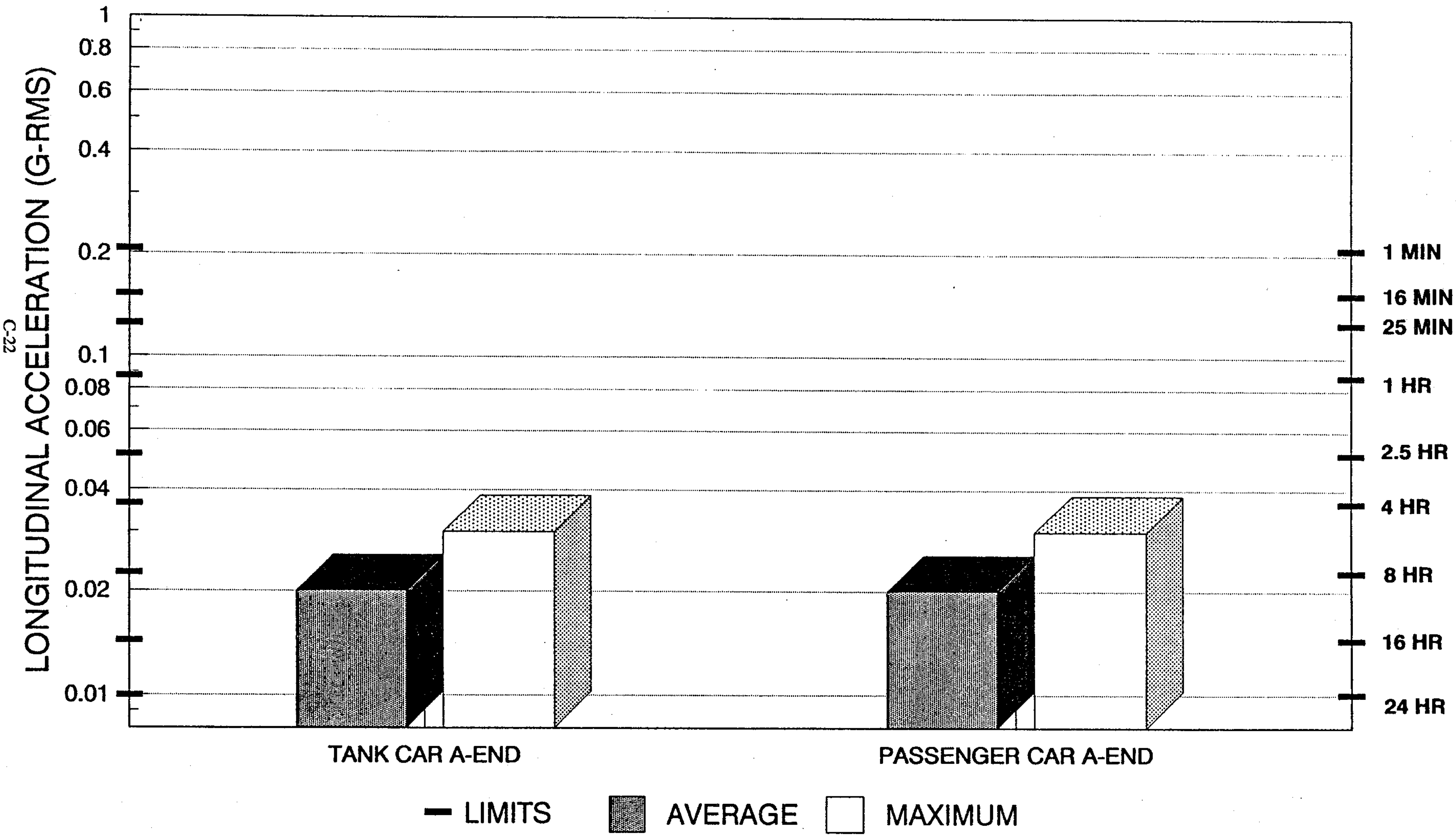



LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
15 - 24 mph Empty Tank Car
LONGITUDINAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR A-END
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

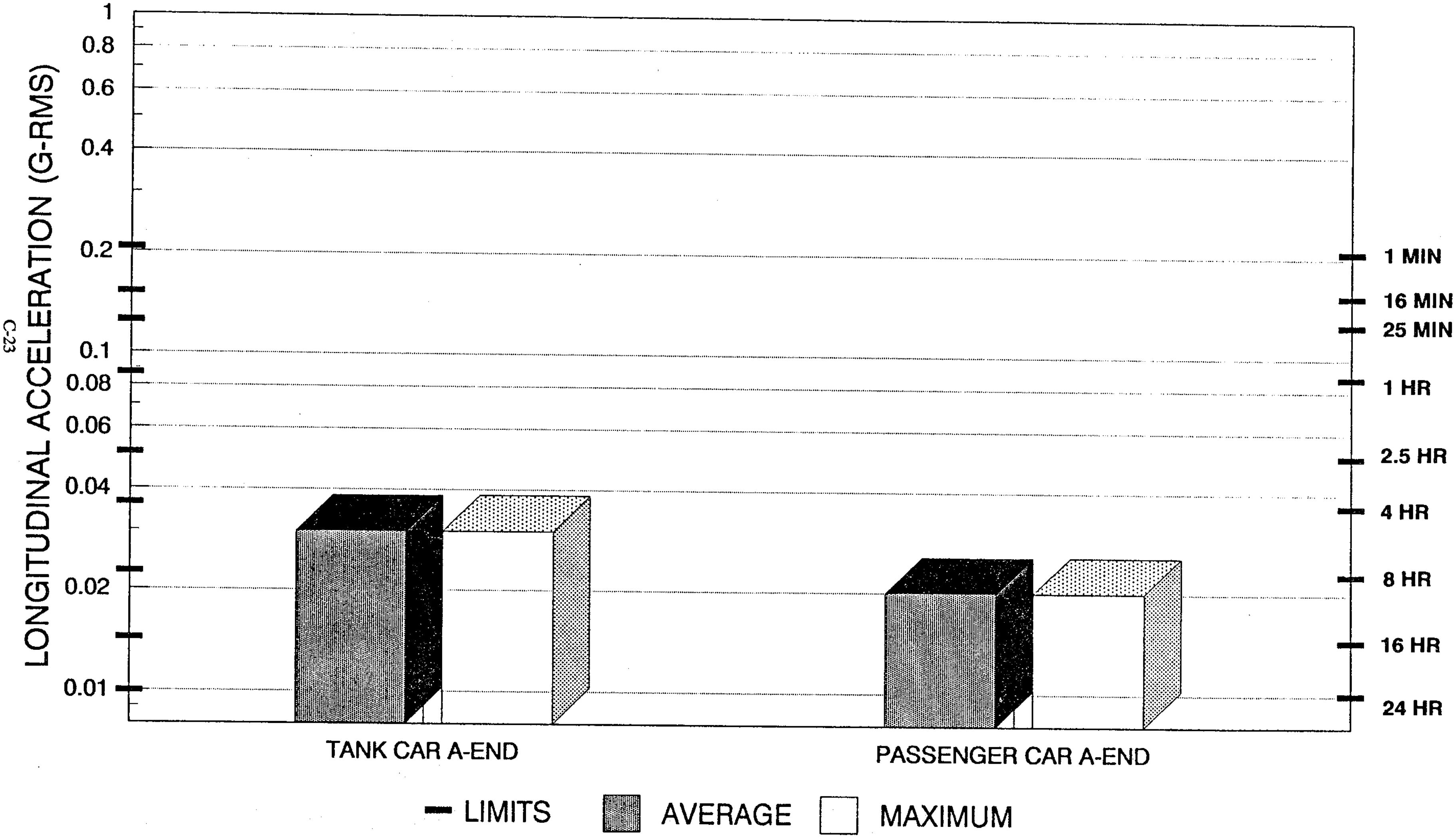
25 - 39 mph Empty Tank Car

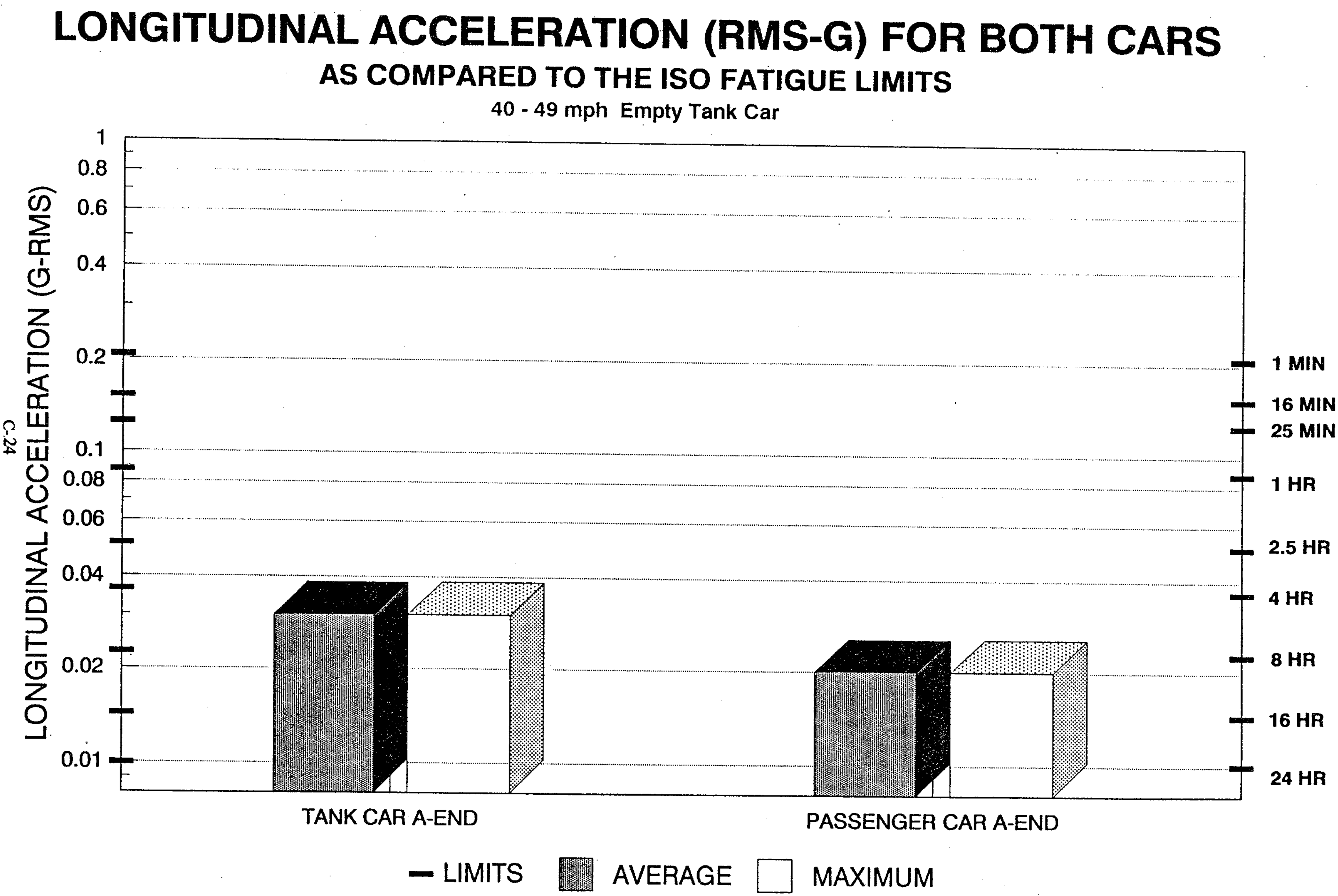


LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS

AS COMPARED TO THE ISO FATIGUE LIMITS

50+ mph Empty Tank Car




LONGITUDINAL ACCELERATION (RMS-G) FOR BOTH CARS
AS COMPARED TO THE ISO FATIGUE LIMITS
40 - 49 mph Empty Tank Car
LONGITUDINAL ACCELERATION (G-RMS)
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
1 MIN
16 MIN
25 MIN
1 HR
2.5 HR
4 HR
8 HR
16 HR
24 HR
TANK CAR A-END
PASSENGER CAR A-END
LIMITS
AVERAGE
MAXIMUM

Appendix D

NTS Tank Car Vibration Investigation Final Report