SUMMARY REPORT

on

STUDY TO DEFINE THE SHOCK AND VIBRATION ENVIRONMENT DURING TRUCK TRANSPORT OF SHIPPING CONTAINERS

to

E. I. du Pont de Nemours & Comapny, Inc.

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by

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STUDY TO DEFINE THE SHOCK AND VIBRATION ENVIRONMENT DURING TRUCK TRANSPORT OF SHIPPING CONTAINERS

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INTRODUCTION

The program of the AEC Division of Reactor Development and Technology will require shipment of experimental fuels in containers ranging in weight from 1000 to 50,000 pounds. The fuel must not be damaged in normal shipment, so that the effects of the experiment may be evaluated without bias. Therefore Du Pont, as a contractor to the AEC for this work, is faced with the task of designing appropriate shipping containers for these experimental setups to protect them during shipment by common carrier.

In order to design these containers efficiently, a shipping system analysis must be performed. One aspect of this analysis is to define the shock and vibration environment typical of the mode of transportation chosen. For the present, it is planned that shipment of the experimental setups will be by one truck from point of origin to destination (to avoid "intermodal shock"), so that shipping design criteria may be based on the environment typical of this mode.

The purpose of this study was, therefore, to establish the shock and vibration environment for containers shipped by commercial truck transport under typical highway conditions, plus occasional rough road and near-accident shock conditions. A literature search was conducted; and from available data, maxima of shock and vibration accelerations were established.

SUMMARY AND CONCLUSIONS OF STUDY

A search of the currently-available literature was conducted to collect information on the truck transport shock and vibration environment.

Based on available data, the following specific conclusions are made:

(1) Definition of Environment. Truck transport shock can be characterized as a recurrent, decaying sinusoidal pulse at frequencies below 20 Hz. Continuous background vibration has been shown to be random, with a Gaussian amplitude distribution. Certain events have a high shock damage potential, particularly dips, bumps, chuckholes, and railroad crossings at high speed. Dips, bumps and holes appear to have greater damage potential for cargo with natural frequencies below 15 Hz, while railroad tracks have higher damage potential for cargo with higher natural frequencies. Similarly, the response severity at the cargo as a function of speed depends to a great extent on cargo natural frequency: low speeds have greater effect on low natural-frequency cargo, and vice versa. In the 10-Hz "recurrent shock" region, truck transport presents a more severe environment than rail transport, while at higher frequencies (above 100 Hz) the rail shock environment becomes more severe. For massive cargos such as the radioactive materials containers, with natural frequencies in the 3-60 Hz range, neither mode presents a distinct advantage, unless special suspensions (air or elastomeric truck suspensions) or special handling are employed.

(2) Axis of Response. The vertical predominates as the axis with the highest potential for damage due to high-amplitude shock and vibration levels...except, of course, in the event of an accident. Peak accelerations may range from 50 percent to 200 percent higher in the vertical than in either the lateral (transverse) or the longitudinal axes for typically severe transient shock events. From a comparison of limited field data, vibration levels in the two horizontal axes may be as much as an order of magnitude less than vertical vibration. The most severe location for vertical accelerations is usually over the rear axles (truck or trailer), although higher acceleration peaks and power spectral density have been recorded in some instances over the fifth wheel...it apparently depends on the tractor suspension, trailer geometry, fifth wheel design and condition, and load configuration. Midspan of the trailer is generally the least severe at most frequencies.

(3) Effects of Load. The most apparent effect of load is to reduce high frequency response components (structural resonances) while accentuating the low frequency response (sprung mass). A concentrated load such as the

nuclear material shipping casks produces a marked increase in low frequency (1-20 Hz) response over that of the empty vehicle. Longitudinal and lateral response levels, however, are generally lower with the loaded vehicle than the empty. Location and configuration of load were noted to have some effects on response level and spectrum shape, but trends were not clearly defined in the literature due to the load structural complexity.

(4) Type of Vehicle. There is insufficient data obtained under similar enough conditions to define clearly the response differences between vehicles (truck versus tractor-semitrailer, for example). However, obvious differences between supposedly identical vehicles were noted. Condition of the suspension system can radically change the acceleration spectrum at the cargo space...if the malfunction involves binding or friction, the high-frequency components are accentuated, the low frequencies reduced. Conversely, worn shocks (low damping) will accentuate the low frequencies in the sprung and unsprung mass resonant frequency range.

(5) Data Format. Data are generally reported in mixed form: shock and vibration lumped (inconveniently) together. Only by statistical analysis of acceleration data can the peak values be assigned the proper frequency/amplitude distribution "family". A great deal of data is reported simply as peak amplitude and (sometimes) dominant frequency for a given event or condition. This gives only shock response. Shock is also described in terms of shock response spectra, which may be viewed as the peak acceleration of an idealized structure (cargo) in response to the given transient event. A third method of presenting data is by means of the power spectral density (PSD) plot, which provides a measure of acceleration power versus frequency in the shock/vibration environment. Akin to this is the acceleration amplitude spectral density. To combine the best features of these methods of data presentation, Sandia Corporation(1) is now using a power spectral density envelope of the random background vibration, plus three-sigma peak values (99.7 percent of the distribution equal or less in amplitude) in particular frequency bands.

(1) SC's most recent transport vibration envelopes are to be presented at a symposium at the University of Wisconsin in December, 1971.

(6) Tie-Down Methods. In protecting cargo by "decoupling" from the truck bed, the pad (or shock mounts), cargo and tie-downs act as a spring-mass-damper system. Successful isolation depends on either broadening the response spectrum (relatively high damping) or tuning the isolation system to a natural frequency removed from the important excitation frequencies of the truck bed. If the isolation system natural frequency falls close to one of these excitation frequencies, amplification will occur at that frequency.

(7) Acceleration Shock and Vibration Envelopes. Based on the available data, the shock and vibration envelopes of Figure 1 were established for both the standard leaf-spring suspensions and the air ride suspensions. The recurring shock limits represent 99.9 percent of the expected peaks (the air ride shock limit is a conservative estimate based on very limited data); while the continuous random vibration limits represent the three-sigma (99.7 percent) envelope of the Gaussian amplitude distribution. These envelopes include both the loaded and empty (lightly-loaded) vehicle, and truck and tractor-semitrailer configurations. For design purposes, the longitudinal and lateral axes may be assumed conservatively to fall within these acceleration limits.

RESULTS OF THE STUDY

Background

At the beginning of this study, a literature search was conducted by Battelle's library staff through the abstracts of The Engineering Index, the Applied Science and Technology Index, and the Industrial Arts Index. References to vehicle ride quality, vehicle vibrations and suspension systems were noted, and the most promising references were obtained. Material on hand in the Mechanical Dynamics Division library was reviewed, including The Shock and Vibration Bulletin of the Naval Research Laboratory. This publication was found to be the best single source of information on transportation shock and vibration.

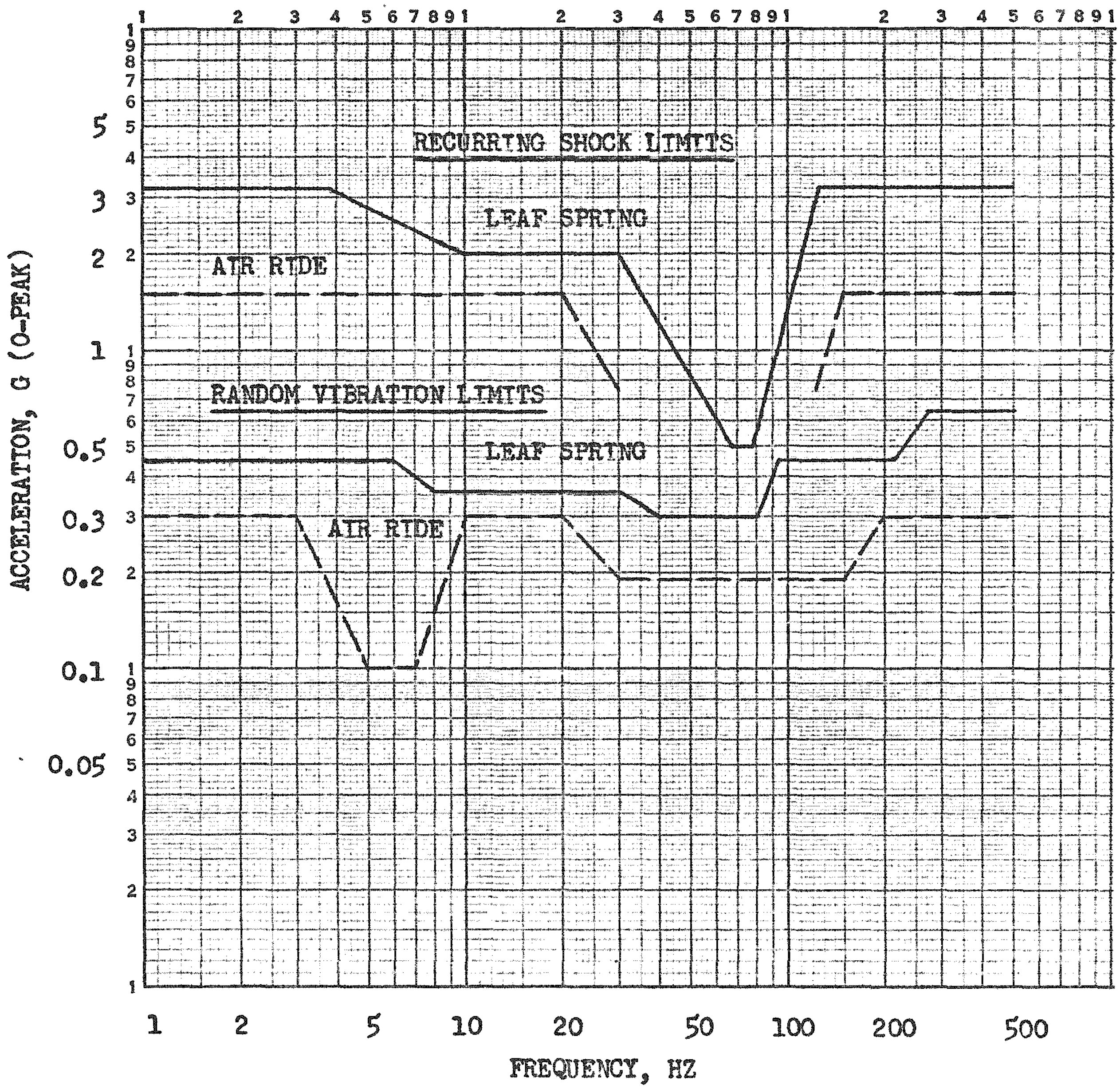


FIGURE 1 . MAXIMUM SHOCK AND VIBRATION ENVELOPES FOR VERTICAL AXIS AT CARGO FOR THE TWO BASIC TRUCK SUSPENSION SYSTEMS

A basic source of information is the Shock and Vibration Handbook[1,2], which defines the important causes of vibration in the vehicle. The primary source of excitation is road irregularities providing a displacement input to the tires and forcing three elastic systems to vibrate:

(1) The vehicle body on main springs (1-4 Hz range)

(2) The unsprung masses (wheels, axles, drive train on tires and main springs...7-20 Hz range)

(3) Structural members (broad frequency range).

Additional sources of vibration are wheel unbalance, and drive train and engine dynamics. All of these sources combine to present a vibration spectrum from one to perhaps 1000 Hz.

Most of the information in the Shock and Vibration Handbook on vehicle response, in fact most of the information published prior to 1965, is concerned with vibration levels at the driver location, with little devoted to shock and vibration at the cargo. This paucity of information led to the establishment of a Data Bank[3,4] by the Sandia Corporation, so that raw data from many sources could be gathered and evaluated. The Data Bank consists of entries on microfilm mounted on aperture cards, with a computerized indexing and retrieval program. Entries consist of abstracted written material and data in the form of graphs or charts. From this collection of data, environmental descriptions of the specific transportation modes can be generated, with periodic re-evaluation possible as new data is obtained.

These, then, were the most important sources of information on which the results of this study are based: technical papers published in the Shock and Vibration Bulletin (NRL), published reports of specific research projects, and information from the Environmental Data Bank (SC).

Data Format

The format by which shock and vibration data are presented is critical in establishing the degree of usefulness of the information. A common technique used in the absence of mechanized data reduction methods is the oscillographic record. An acceleration time-history is recorded, for example, and the resulting trace scanned for maxima and predominant frequencies. Much of the available information on truck ride quality is reported in this manner of analysis, with conditions under which the recorded maximum accelerations occurred seldom specified in detail.

A survey by Sandia Corporation personnel[4] showed that to be most useful the data should be graphical in format and statistical in nature. To achieve this end Sandia Corporation developed the VIBRAN ("vibration analysis") data reduction system, which processes a sample of an acceleration time-history recorded on magnetic tape and presents the data in terms of peak acceleration probability densities within selected frequency bands. A typical example of the VIBRAN format is shown in Figure 2, in this case presenting data for a 2-1/2-ton truck in off-highway operation[5,6]. The vertical columns in the figure represent narrow frequency "windows" that exclude components in other frequency bands. The rows, then, are amplitude bands in which acceleration peaks are counted. For example, the number "5.89" in the 0-5 column represents the fact that two peaks out of a total of 34 peaks in the 0 to 5 Hz frequency band (2/34 x 100 = 5.89 percent) fell above 2.3 g, but below 3.2 g, during the given event.

To combine the VIBRAN records of specific events into a "trip composite", a generalized computer program called VIDAR (Vibran Data Reduction) was developed. The resulting composite probability distribution of peak acceleration amplitude is then based on load, location of load, frequency of occurrence of road type or event, and most probable speed for the road type considered. A list of road types and events, with frequency of occurrence and expected speed, based on extensive field data[7] is given in Table 1. This list presents sixteen conditions recognized by observers during the 55 hours of over-the-road data recorded during a trip from Ft. Eustis, Virginia, to Albuquerque, New Mexico. Voice commentary was added to the continuously-recorded data (thirteen 2500-foot rolls of magnetic tape) at five minute intervals, or when special events occurred. From this commentary, a "weighting" of events as shown in Table 1 was possible.

Certain events in the transport environment are transient, lasting at most a second or two: for example, the truck crossing a railroad track, hitting a dip, bump, or chuckhole. One method of characterizing a transient

ACCELERATION DISTRIBUTION, PERCENT

Driving off road in desert brush.

0-PEAK ACCELERATION (g)	0-5	5-10	10-20	20-30	30-45	45-60	60-87	87-125	125-175	175-250	250-350
3.2	3.89										
2.3	0.00										
1.65	2.94										
1.2	0.00										
0.86	0.00										
0.62	0.00										
0.45	0.00	1.36									
0.32	5.93	9.44					0.52				
0.23	14.68	16.19					10.53		0.42	0.60	0.70
0.17	35.29	24.34	1.76	0.78	0.15		4.69		3.01	5.95	0.00
0.12	14.68	16.20	11.85	3.01	1.92		0.13	0.10	8.81	15.45	0.85
0.10	20.61	32.46	86.39	96.27	97.88	99.90	84.05	99.85	87.71	77.25	99.15
Frequency CPS	0-5	5-10	10-20	20-30	30-45	45-60	60-87	87-125	125-175	175-250	250-350
No. of Peaks Counted	34	74	227	401	622	837	769	1701	2321	3270	4770

Total No. of Peaks Counted: 15,026

FIGURE 2 . EXAMPLE OF "VIBRAN" FORMAT OF ACCELERATION DATA PRESENTATION (REF. 5)

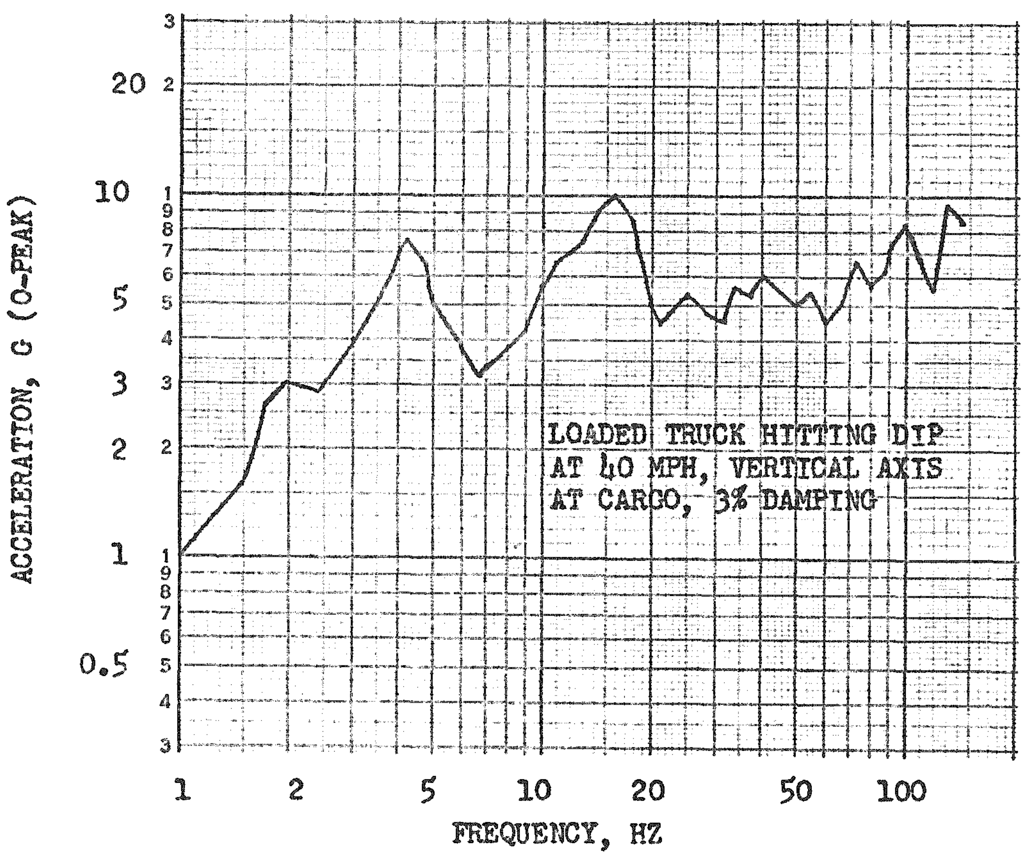


FIGURE 3 . EXAMPLE OF SHOCK RESPONSE SPECTRUM FOR TRANSIENT EVENT (REF. 8)

TABLE 1. FREQUENCY OF OCCURRENCE OF ROAD TYPES AND EVENTS (Ref. 7)

	Range of Speed	Speed Most Frequent (or Severe)	Frequency of Occurrence *
1. Level concrete	30-65	50	21.5%
2. Level blacktop	10-65	30 & 50	21.5
3. Bridge crossings	5-60	45	16.2
4. Railroad crossings	5-50	25 (50)	12.6
5. Blacktop hills	5-10 up 35-58 down	5 (50)	7.0
6. Blacktop over concrete	20-50	(20)	3.6
7. Bumps	20-50	(50)	3.6
8. Tunnels	50	(50)	3.6
9. Asphalt freeways	55-60	60	2.4
10. Parking lots	10-25	(25)	2.4
11. Concrete freeways	50-65	50	1.8
12. Concrete overpasses	30	(30)	1.8
13. Concrete hills	20 up 40 down	(20) (40)	1.2
14. Detours	5-15	(5)	1.2
15. Brick road	15-20	2 1	0.6
16. Unpaved road	30	(30)	0.6
17. Unobserved (including accidents)			0.6

* - Estimated percent of total trip time under given road condition.

event is by determining its shock response spectrum, which is useful for determining how a simple structure (the idealized cargo) will respond to a complex vibrational input. To understand the concept of shock response spectrum, imagine a number of single-degree-of-freedom, spring-mass oscillators to be fastened to the truck, and constrained to move in a single axis of motion. Each oscillator has the same percent of critical damping, but a different natural frequency. The maximum response of each oscillator as excited by the transient motion of the truck body in that axis is plotted as a single point at the particular natural frequency of that oscillator. The series of response maxima constitutes the shock response spectrum, and gives a good representation of the frequency content of the truck body motion. Note that the shock response spectrum does not describe the acceleration versus frequency characteristic of the truck body motion directly, and this is the principal source of misunderstanding by those who are familiar with the use of the Fourier spectrum to describe complex signals.

A typical shock response spectrum [8,9] is plotted in Figure 3 for vertical acceleration of a loaded tractor-flatbed trailer with leaf spring, tandem axle suspension hitting a dip at 40 miles per hours. This event produced the highest peak acceleration response of any transient recorded by Sandia. Note that the peak response was 10 g, whereas an examination of the acceleration time-trace recorded on the truck body showed a maximum of 3.3 g. Damping values for cargo response spectra typically are 3 to 5 percent of critical to represent cargo fastened directly to the truck bed, and 10 percent to represent protected cargo. Zero damping would provide the limiting, worst-case response.

Considering now the same system with continuous sinusoidal excitation rather than a shock excitation, for a comparable peak response of 10 g, the system with 3 percent critical damping (Q = 16.7) requires only 0.6 g peak sinusoidal excitation at the natural frequency. This is why much lower levels of continuous vibration excitation can be as damaging as the high-level transient accelerations.

Another method of characterizing the truck transport acceleration environment is by determining the Power Spectral Density (PSD), which is a measure of the vibratory energy input. Typical PSD plots (in units of acceleration-squared per cycle per second) for three points on the bed of an air suspension van[10] are shown in Figure 4. The power spectral density function for random data describes the general frequency composition of the data in terms of its mean square value[11]. To obtain the mean square value of a data time-history, f(t), as a function of frequency, ω, and bandwidth, $\Delta\omega$, the data signal is first passed through a sharp cutoff, band-pass filter. The resulting signal is squared, then averaged over the period of observation, T, as shown in Figure 5. As the observation time, T, approaches infinity, this averaged value approaches the exact mean square value; and as the bandwidth, $\Delta\omega$, approaches zero, the mean square value approximates the product of bandwidth and the PSD value:

$$\psi^2[\omega, \Delta\omega] \doteq G(\omega)\Delta\omega$$

$$G(\omega) = \lim_{\Delta\omega \to 0} \frac{\psi^2}{\Delta\omega} = \lim_{\Delta\omega \to 0} \lim_{T \to \infty} \frac{1}{\Delta\omega T} \int_{t-T}^{t} x^2(t, \omega, \Delta\omega)dt \quad .$$

Calculation of the power spectral density function therefore hinges upon a choice of practical filter bandwidths, practical observation time lengths, and a minimum practical number of frequency points. The PSD function has several unique properties that make it particularly useful for random data analysis[12]:

(1) Determination of response power spectral density:

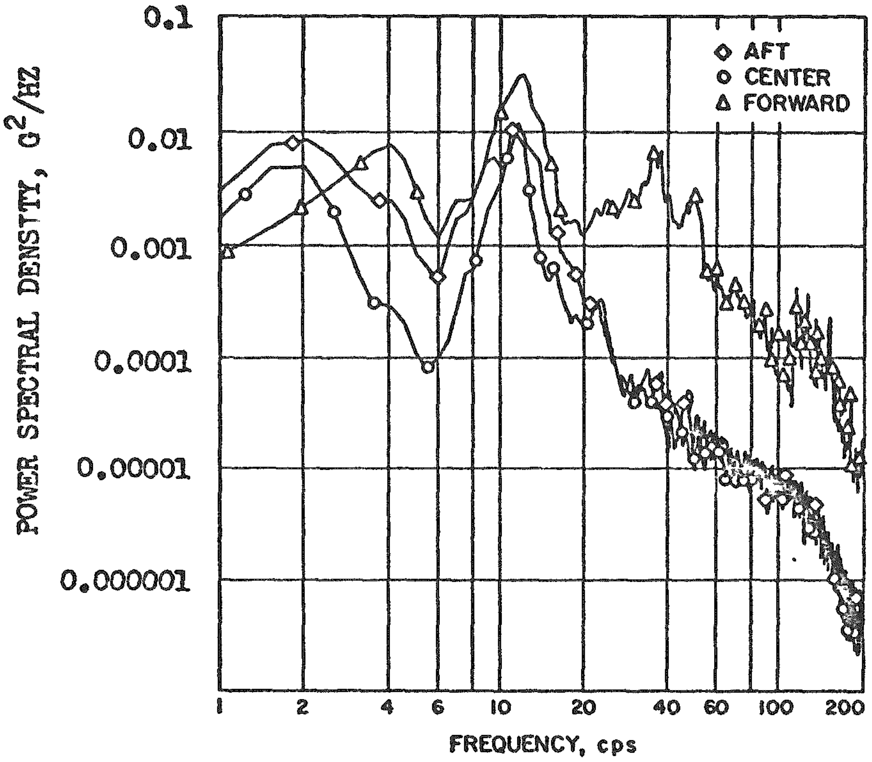
$$S_x(\omega) = \left| H(\omega) \right|^2 S_f(\omega)$$

where

S_f = input PSD

S_x = system response PSD

$H(\omega)$ = system transfer function.



Test—*RA Block III* rough road—aft, center, and forward positions, maximum envelope PSD

FIGURE 4. TYPICAL ACCELERATION POWER SPECTRAL DENSITY PLOT FOR AIR SUSPENSION TRACTOR AND VAN, VERTICAL AXIS AT CARGO (REF. 10)

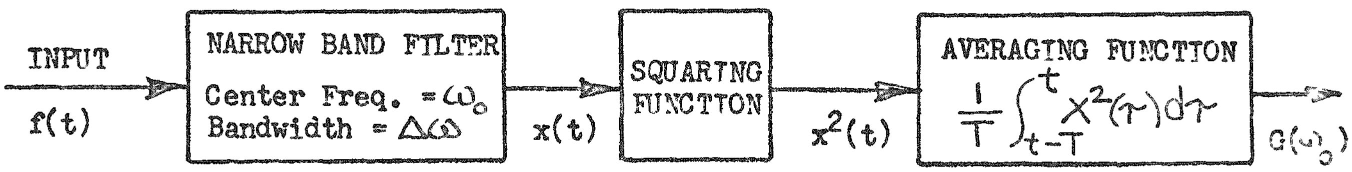


FIGURE 5. BLOCK DIAGRAM OF METHOD FOR DETERMINING POWER SPECTRAL DENSITY FUNCTION, $G(\omega_0)$

(2) Determination of mean square of response:

$$\overline{x}^2 = 1/2\pi \int_0^\infty \left|H(\omega)\right|^2 S_f(\omega)d\,\omega \quad .$$

For example, if the PSD plot were flat ("white noise" acceleration) with an amplitude of G_o (g^2/Hz), the response of a single-degree-of-freedom system would be:

$$\overline{x}^2 = (\omega_n/8\zeta)\ G_o$$

$$g_{rms} = \sqrt{\overline{x}^2}$$

where

ω_n = system natural frequency, rad/sec

ζ = ratio of system damping to critical damping.

RMS acceleration defines the total energy in the complete frequency band; whereas the spectral density defines power at discrete freqquencies within the band. The term "power" may be considered as follows: assume a viscous damper (mechanical "resistor") value, C = 1 lb-sec/in., and a spectral density value of G_o (g^2/Hz) at ω_o. The power dissipated across the damper through the narrow spectrum "window" one hertz wide is then...

$$P = (386)^2 C(1) G_o/\omega_o^2$$

$$= (386)^2 G_o/\omega_o^2 \qquad \text{in.-lb/sec} \quad .$$

Although the PSD plot provides a very useful tool for analysis of dynamic systems under random excitation, it hardly represents the most practical data format for use by the design engineer. Therefore, for this Battelle study zero-to-peak acceleration envelopes were developed, based on the statistical characteristics of the data (this is essentially the same technique used by Ostrem[13] for a recent survey of transportation vibration environments). For data in the VIBRAN and VIDAR formats, the maximum acceleration level including the desired statistical distribution, and the center frequency of the band were used to establish a point on the curve. For data presented as PSD plots, a straight-line envelope was drawn to enclose the spectrum (with a little to spare). An RMS envelope (one-sigma values) was developed directly from this:

$$g_{rms}(f) = \sqrt{G(f)\Delta f},$$

where

$\Delta f = 1$ Hz.

From this RMS curve, three-sigma acceleration envelopes were then drawn (implying that 99.7 percent of all acceleration peaks would fall on or beneath this envelope). Recent work by the Sandia Corporation has shown the amplitude distribution of acceleration peaks recorded on the truck bed to be Gaussian random up to very nearly 99 percent of the sample, plus a few higher peaks in an obviously-different distribution. By calling these latter peaks "recurring shock", envelopes for continuous random vibration based on the Gaussian distribution were developed. These are shown in Figure 6, along with envelopes of recurring shock peaks, and the response envelope of a typical lightly-damped cargo. Acceleration envelope curves in the following sections based on VIBRAN data do reflect some recurring shock, and consequently present higher peak levels than the continuous vibration curves of Figure 6.

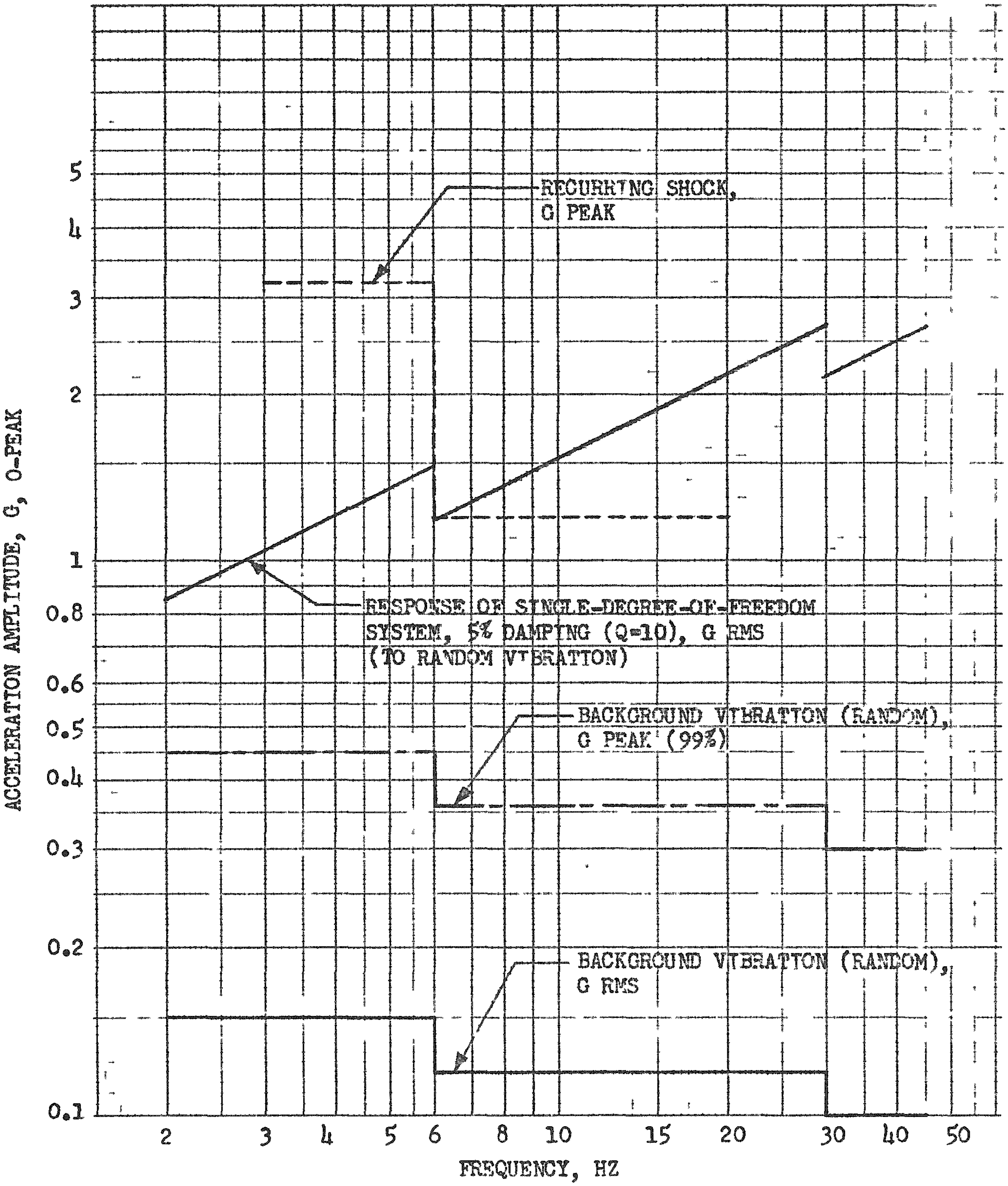


FIGURE 6. TRUCK TRANSPORT ACCELERATION ENVELOPE BASED ON SANDIA LABORATORIES DATA BANK

Maximum Transient Accelerations

Much of the available material on tractor-semitrailer ride quality reports the maximum recorded acceleration, with conditions under which this maximum occurred seldom specified in detail. Acceleration maxima along the major orthogonal axes for more-or-less specific conditions are listed in Table 2 for a standard flatbed trailer (tandem axles) with leaf spring suspension[14-17]. Shock levels in the vertical axis predominate in most events, with the greatest potential for damage in this direction. Substantially lower levels of acceleration are attained by use of an air spring or elastomeric suspension system. For example, comparisons are made in Table 3 of the vertical acceleration maxima of four suspension systems under conditions somewhat comparable to those of Table 2[18]. In Table 4 further comparison is made between an air ride suspension and two leaf spring suspensions over a 3500-foot stretch of unspecified road[19]. Similarly, the results of a series of tests with a van equipped first with a leaf spring suspension, then with an air suspension, over a bump 3-1/2 inches high and 12 inches long are given in Table 5.

Shock Response Spectra

The shock response spectra for several representative transient events have been determined, using accelerations recorded on a tractor-flatbed trailer combination[8]. Major peaks in these response spectra are listed in Table 6 to provide some idea of the maximum acceleration experienced by the idealized structure (cargo). Note that the loaded truck hitting the dip at 40 miles per hour presents the most severe case recorded, and results in a maximum 10 g at the wheel-hop frequency of 16 Hz. Even protection of the cargo (10 percent of critical damping) does not significantly reduce the acceleration effects of this shock.

A maximum shock response spectra "envelope" has been determined[10] for an air suspension van, based on data samples of 21 shock spectra recorded at the worst (aft) vertical position. Major peaks of 4.0 g (at 18 Hz), 3.5 g (30 Hz) and 4.0 g (63 Hz) were determined for 5 percent of critical

TABLE 2. MAXIMUM TRANSIENT ACCELERATIONS ON SEMITRAILER WITH STANDARD LEAF SPRING SUSPENSION

Ref.	Condition	Maximum Acceleration, G Vertical	Lateral	Fore/Aft
14	City route RR crossing[1]	1.15	1.10	0.40
14	Rough streets[1]	1.35	1.15	0.55
14	Simulated rough road, 9 mph[1]	3.4	1.55	1.75
14	Emergency stop from 45 mph[1]	0.43	0.18	1.2
14	High-speed wheel unbalance[1]	0.50	0.55	0.33
15	Ungraded road, 30 mph	1.5	1.0	0.5
15	Graded road, 30 mph	1.0	0.25	1.0
16	Empty, concrete highway, high speed	2.7		
17	Concrete highway at 50 mph[2]	1.50	<1.00	<1.00
8	RR track at 40 mph[2]	1,9	0.6	0.8
8	Dip at 40 mph[2]	3.3	0.8	2.3
8	Empty, RR track at 40 mph	2.3		0.8
8	Empty, dip at 40 mph	1.9		0.8

1 - 11,310-lb payload
2 - 28,190-lb payload

TABLE 3. A COMPARISON OF MAXIMUM ACCELERATIONS RECORDED FOR SEVERAL TRACTOR/TRAILER SUSPENSION SYSTEMS (Reference 18)

	Peak Vertical Acceleration				
	Trailer-Leaf Spring		Trailer-Air Spring		
Tractor	Front	Rear	Front	Rear	
A	0.83g	0.97g	0.62g	0.75g	RR Crossing Shock
B	0.37	0.97	0.31	0.69	RR Crossing Shock
C	1.23	1.03	0.98	0.81	RR Crossing Shock
D			0.55	0.69	RR Crossing Shock
A	0.60	0.92	0.50	0.57	Bridge Shock
B	0.49	1.07	0.31	0.69	Bridge Shock
C	0.68	1.30	0.98	0.81	Bridge Shock
D			0.55	0.69	Bridge Shock
A	0.31	0.43	0.25	0.25	Highway Vibration
B	0.21	0.31	0.12	0.25	Highway Vibration
C	0.55	0.43	0.49	0.37	Highway Vibration
D			0.25	0.25	Highway Vibration

Tandem drive-axle tractors

(A) White Velvet Ride (rubber torsion)
(B) Neway Air Ride (air sponge, rigid trailing arm)
(C) Hendrickson Shear Ride (rubber shear)
(D) Peterbilt Stabilaire (steel leaf and air spring)

Course - 43 miles including RR tracks, bridges, primary blacktop roads, expressways--50 mph.

Load: Front axle - 10,070 lb; tandem drive axles - 31,280 lb; tandem trailer axles - 23,720 lb.

TABLE 4. A COMPARISON OF RIDE QUALITY WITH AIR RIDE VERSUS STEEL SPRING SUSPENSIONS (Ref. 19)

			Peak Accelerations			
			Trailer Rear			Trailer Front,
	f_n	Speed	Vert.	Lat.	Long.	Vertical
Air Ride	2.0 Hz	40	0.58g	0.25g	0.90g	0.87g
		50	0.67	0.42	0.83	0.83
Multi-Leaf Spring	3.3 Hz	40	1.34	0.25	1.33	1.17
		50	1.66	0.33	1.50	1.50
Single-Leaf Spring	3.3 Hz	40	1.66	0.67	0.83	1.33
		50	1.75	0.68	1.50	1.33

Load: Distributed with 12,400 lb at rear axle.

TABLE 5. SHOCK RESPONSE COMPARISON OF A VAN EQUIPPED WITH STEEL SPRING SUSPENSION VERSUS AN AIR SUSPENSION, SINGLE BUMP 3-1/2 INCHES HEIGHT (BARNES AND REINECKE FOR MAYFLOWER VAN LINES)

		Peak Acceleration (Vertical Axis)		
	Load	5 mph	20 mph	40 mph
Steel Spring Suspension	6,000 lb	+3.5/-3.1 g	+1.25/-1.5 g	+1.75/-1.75 g
	12,000 lb	+1.3/-1.0	+1.0/-1.2	+1.7/-1.2
	24,000 lb	+0.75/-0.75	+0.8/-0.9	+2.0/-1.6
Air Suspension	6,000 lb	+0.6/-0.7 g	+0.6/-0.75 g	+1.0/-1.0 g
	12,000 lb	+0.5/-0.5	+0.5/-0.5	+1.25/-1.0
	24,000 lb	+0.5/-0.35	+0.5/-0.5	+1.0/-0.75

TABLE 6. MAJOR PEAKS IN SHOCK RESPONSE SPECTRA FOR TRANSIENT EVENTS, TRACTOR-FLATBED SEMI-TRAILER WITH TANDEM-AXLE LEAF SPRING SUSPENSION (Ref. 8)

Transient Event	Damping	Shock Response Maxima (g) Vertical	Lateral	Longitudinal
Loaded truck, RR track at 40 mph	3%	2.2 (4.1 Hz)	0.4 (9 Hz)	0.5 (9 Hz)
		3.5 (10)	1.25 (14)	0.8 (17)
		3.9 (17)	1.5 (31)	1.4 (25)
		4.5 (25)	1.7 (55)	1.2 (55)
Loaded truck, dip at 40 mph	3%	7.2 (4.1)	0.9 (17)	1.1 (4.1)
		10 (16)	1.5 (28)	1.5 (15)
		6.0 (41)	1.7 (60)	2.1 (31)
	10%	4.3 (4.1)	0.47 (17)	0.72 (4.5)
		7.2 (16)	1.25 (50)	1.0 (13)
		4.7 (40)		1.6 (31)
Empty truck, RR track at 40 mph	3%	3.2 (3.7)		0.4 (6)
		3.9 (11)		0.98 (13)
		4.1 (16)		1.2 (17)
Empty truck, dip at 40 mph	3%	3.9 (4.1)		0.52 (6)
		3.0 (8)		0.9 (8)
		4.8 (15)		1.6 (17)
		4.0 (21)		1.0 (41)
		3.2 (67)		

damping (Q = 10). Assuming the same representative highway conditions were sampled, substantial mitigation of shock acceleration levels is shown with the air suspension system.

Maximum accelerations from response spectra generated for a 2-1/2 ton flatbed truck under typical conditions are tabulated in Table 7[5]. Note that the near-accident condition (backing into the loading dock) is much less severe than shock conditions more often encountered, such as driving over potholes at a truck stop.

Peak Acceleration Envelopes

Data from which the acceleration envelopes of Figure 7 were developed were recorded during shipment of a radioactive materials cask from Wilmington, Delaware to Albuquerque, New Mexico[7,16]. These envelopes represent a statistical analysis of the composite of trip sample events, weighted according to the frequency of occurrence (see Table 1). Peaks occurring with frequency less than 0.1 percent of the total sample number have been omitted. For this study a tractor and flatbed semitrailer with tandem axles and leaf spring suspension were used.

As an interesting contrast, data from a similar study undertaken two years later are shown in Figure 8. In this study[8,9,17] a similar tractor, flatbed trailer combination was used, but the trailer was reinforced and "renewed". Typical events were sampled on the trip from Oak Ridge, Tennessee to Paducah, Kentucky, and the trip composite determined from previously-established weighting factors. A radically different spectrum resulted from this data, with much higher shock and vibration levels occurring at lower frequencies, and much lower levels at frequencies above 80 Hz. Several factors could account for these differences: (1) flexibility of the first flatbed trailer tending to reduce mid-range frequency response, (2) improved suspension action (lower friction) of the renewed trailer resulting in amplification at the sprung and unsprung mass natural frequencies, but attenuation at higher frequencies, (3) supposedly comparable, but actually more severe sample events, or (4) improvements in instrumentation and data analysis techniques.

TABLE 7. MAJOR PEAKS IN SHOCK RESPONSE SPECTRA FOR TRANSIENT EVENTS; 2-1/2-TON FLATBED TRUCK WITH LIGHT LOAD (Ref. 5)

Transient Event	Peak g at Truck Bed	Damping	Axis	Response Spectrum Maxima, g
Backing into	0.8	3%	Longi-	0.7 (2.1 Hz)
loading dock			tudinal	1.4 (5)
			(forward)	2.1 (10)
				1.7 (14)
	0.5	3%	Vertical	1.25 (5.5 Hz)
			(aft)	0.9 (10)
				1.15 (28)
				1.1 (60)
Driving across RR	2.2	3%	Vertical	2.7 (2.9 Hz)
tracks at 50 mph			(aft)	2.8 (4.5)
				2.4 (11)
				3.6 (40)
				4.3 (70)
Driving across cattle	2.3	3%	Vertical	3.9 (2.3 Hz)
guard at low speed			(aft)	4.8 (3.5)
				6.1 (10)
				5.0 (55)
Driving across pot-	3.4	3%	Vertical	7.5 (2.6 Hz)
holes at truck stop			(aft)	4.2 (6)
				4.7 (10)
				4.5 (28)
				4.6 (55)

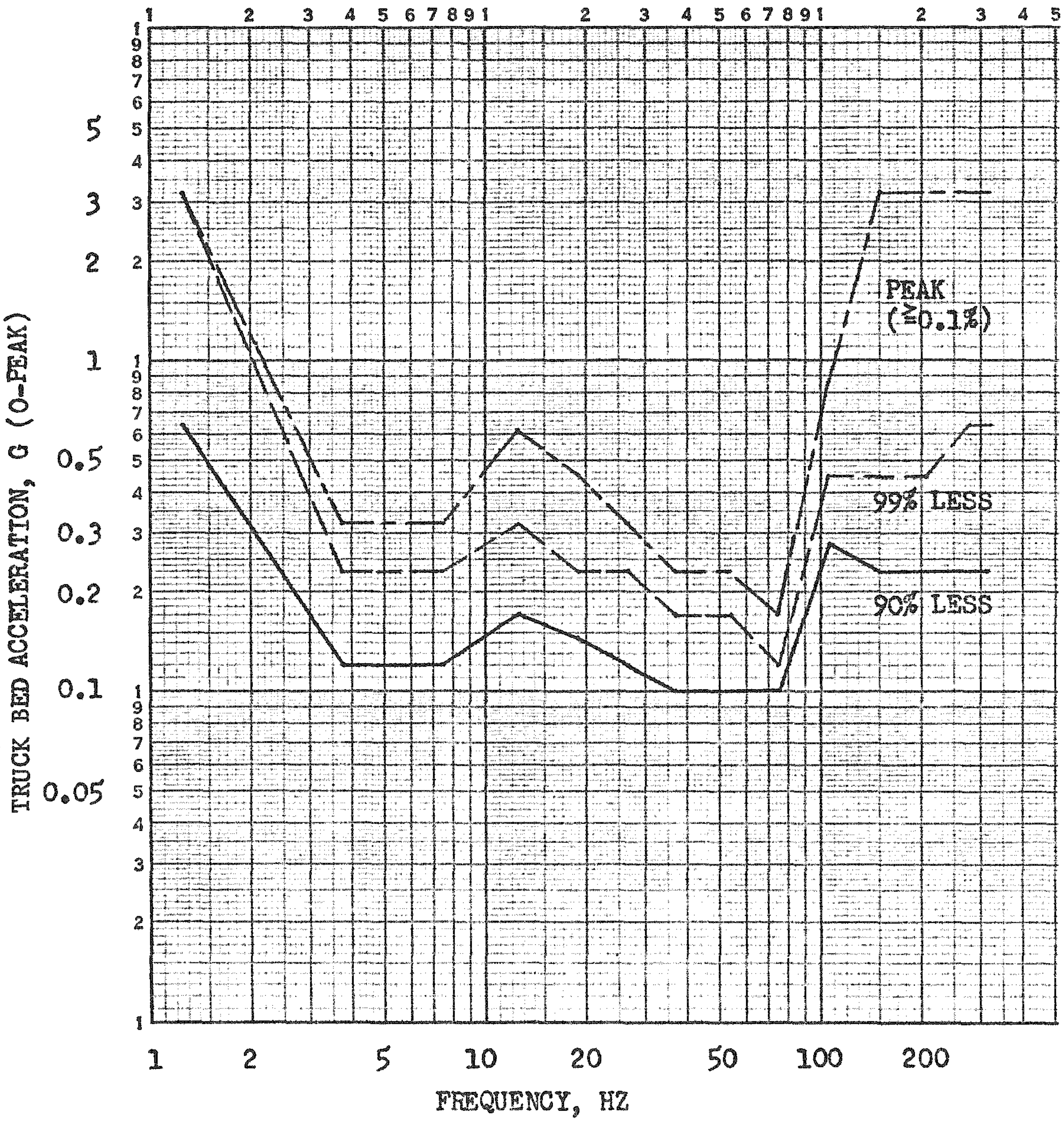


FIGURE 7 . ACCELERATION ENVELOPES FOR VERTICAL AXIS AT CARGO SPACE, TRACTOR AND FLATBED SEMI-TRAILER, TANDEM AXLE WITH LEAF SPRING SUSPENSION, LOADED WITH 15-TON CASK. (REF. 7)

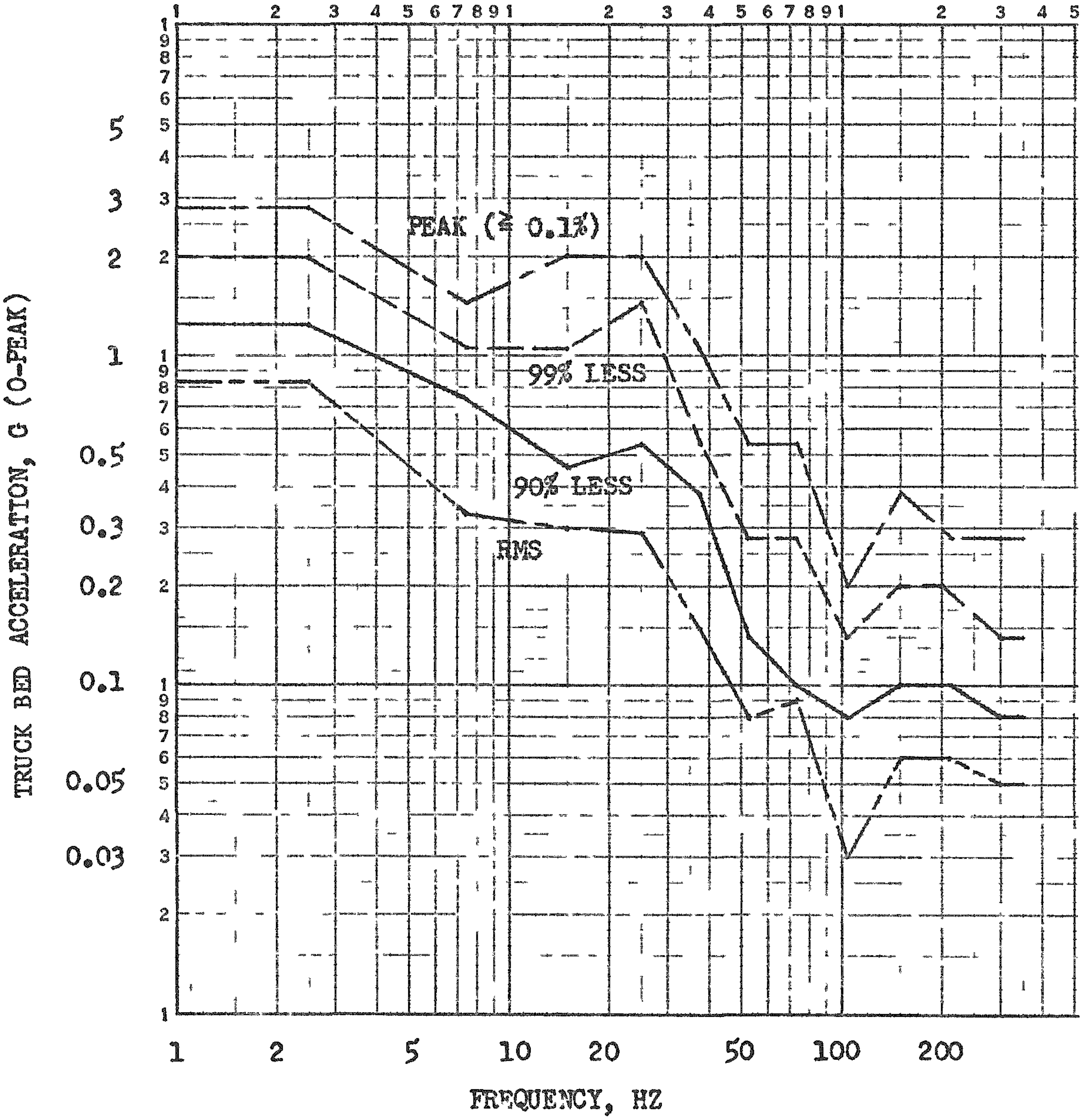


FIGURE 8 . ACCELERATION ENVELOPES FOR VERTICAL AXIS AT CARGO SPACE, TRACTOR AND FLATBED SEMI-TRAILER (RENEWED), TANDEM AXLE WITH LEAF SPRING SUSPENSION, LOADED WITH 15-TON CASK (REF. 8)

Comparing the action of the empty truck, Figure 9, leads to the conclusion that load had relatively little effect on shaping the peak response curve for either truck, although both show generally lower response levels at low frequencies (and higher at high frequencies) when empty. The pronounced peak at the wheel-hop frequency (15 Hz) for the renewed trailer is evidence that the response difference is most probably due to major differences in suspension action between the two trucks. Schock and Paulson[21] report that vibration levels are practically unaffected by load in the lower frequency range, although the higher frequency components are reduced by load. This may be true for more generalized cargo, but the data collected for the more concentrated load presented by the casks show a pronounced increase in low frequency response.

A comparison of peak accelerations measured along the three major axes, Figure 10, shows the vertical response to predominate, confirming previous conclusions drawn from the tabulated acceleration maxima. Higher longitudinal response was recorded with the empty, renewed trailer in the 150-350 Hz range. For the most part, longitudinal and lateral responses were found roughly comparable, although for certain singular events (the loaded truck hitting the dip at 40 mph, for example) the longitudinal axis showed significantly higher shock and vibration levels.

A comparison of peak accelerations in the vertical axis on the bed of a 2-1/2-ton truck is given in Figure 11 for composites of "normal" and "abnormal" events. The abnormal events have not been statistically weighted (the curve then tends to fall beneath the "normal"). Events included in the abnormal are such transients as collision with the loading dock, crossing railroad tracks or cattle guards at high speed, and hitting potholes in the unpaved area of a truck stop at high speed[5]. The truck was lightly-loaded.

Vertical acceleration levels at representative locations in an air suspension van were measured during transport of spacecraft components from Pasadena, California to Cape Kennedy, Florida[10,20]. The tractor and tandem-axle van were ballasted to the nominal load rating to improve dynamic characteristics. About 85 percent of the travel was on smooth highways, but rough roads (detours, etc.) were also sampled. Power spectral density plots were obtained for several loads, with apparent differences due to load

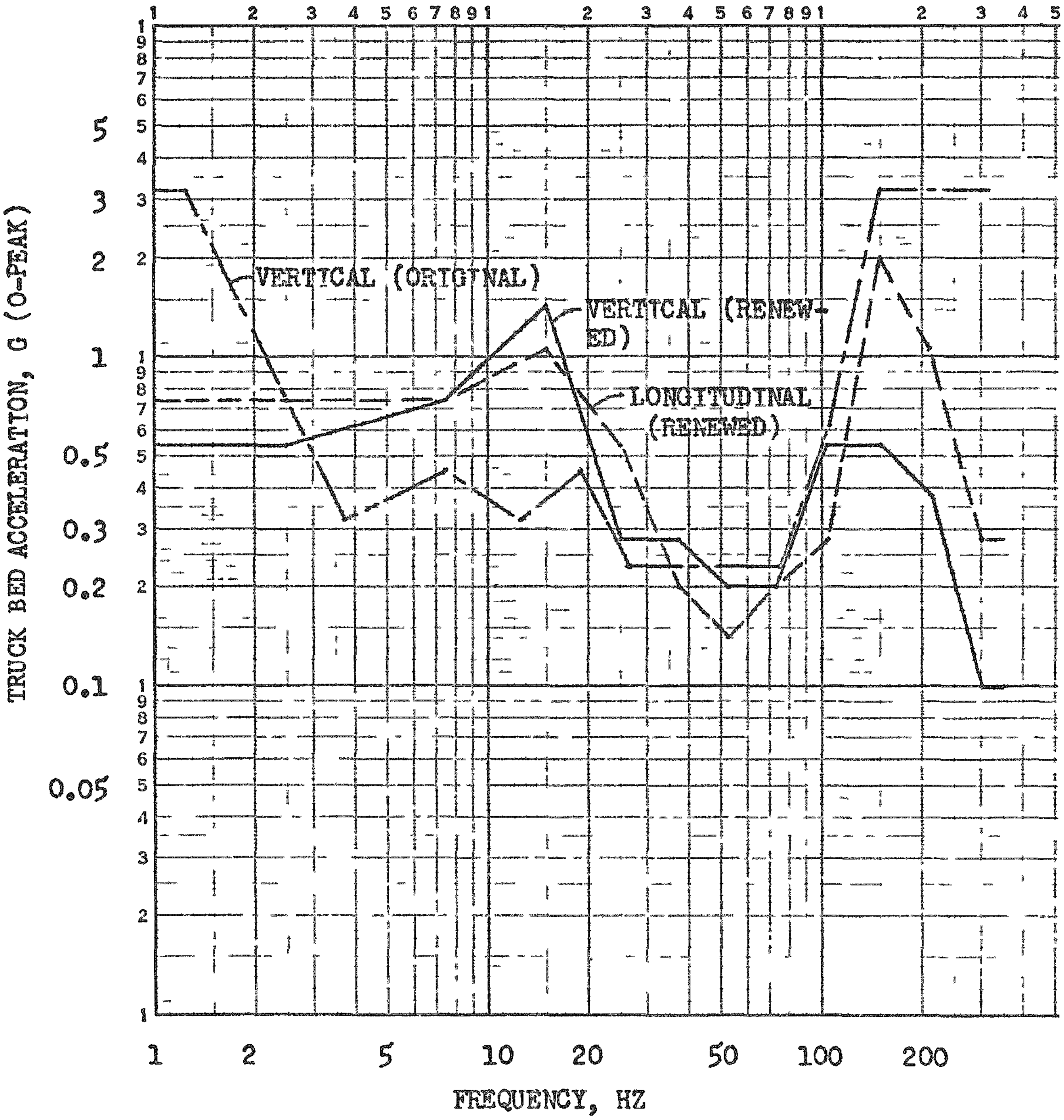


FIGURE 9. COMPARISON OF PEAK ACCELERATIONS (≧ 0.1%) AT CARGO SPACE ALONG MAJOR AXES, TRACTOR AND SEMI-TRAILER, TANDEM AXLE WITH LEAF SPRING SUSPENSION, LIGHTLY LOADED (REF. 8)

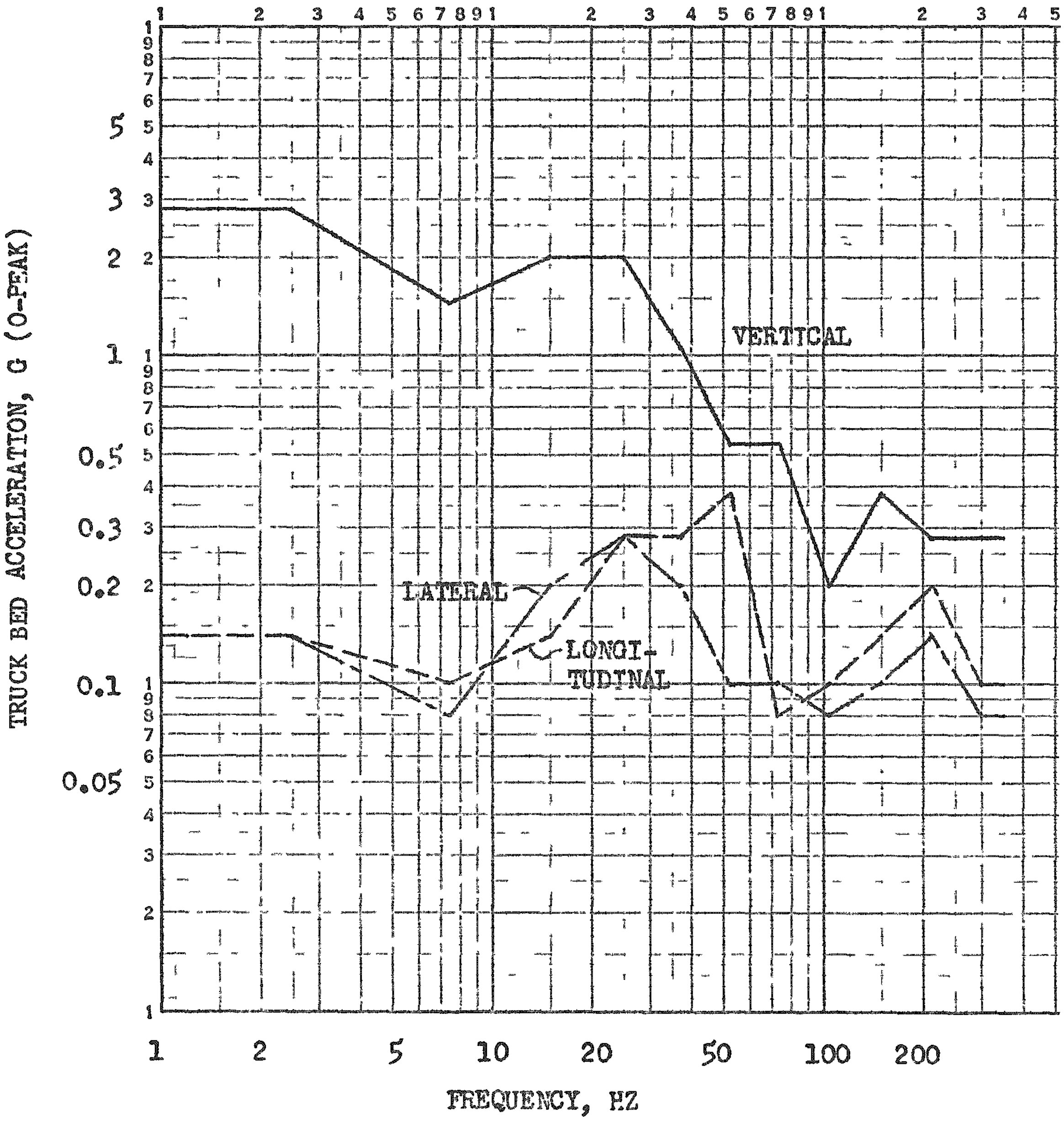


FIGURE 10. COMPARISON OF PEAK ACCELERATIONS (≧ 0.1%) AT CARGO SPACE ALONG THE MAJOR AXES, TRACTOR AND FLATBED SEMI-TRAILER WITH TANDEM AXLE, LEAF SPRING SUSPENSION (RENEWED), LOADED WITH 15-TON CASK (REF. 8)

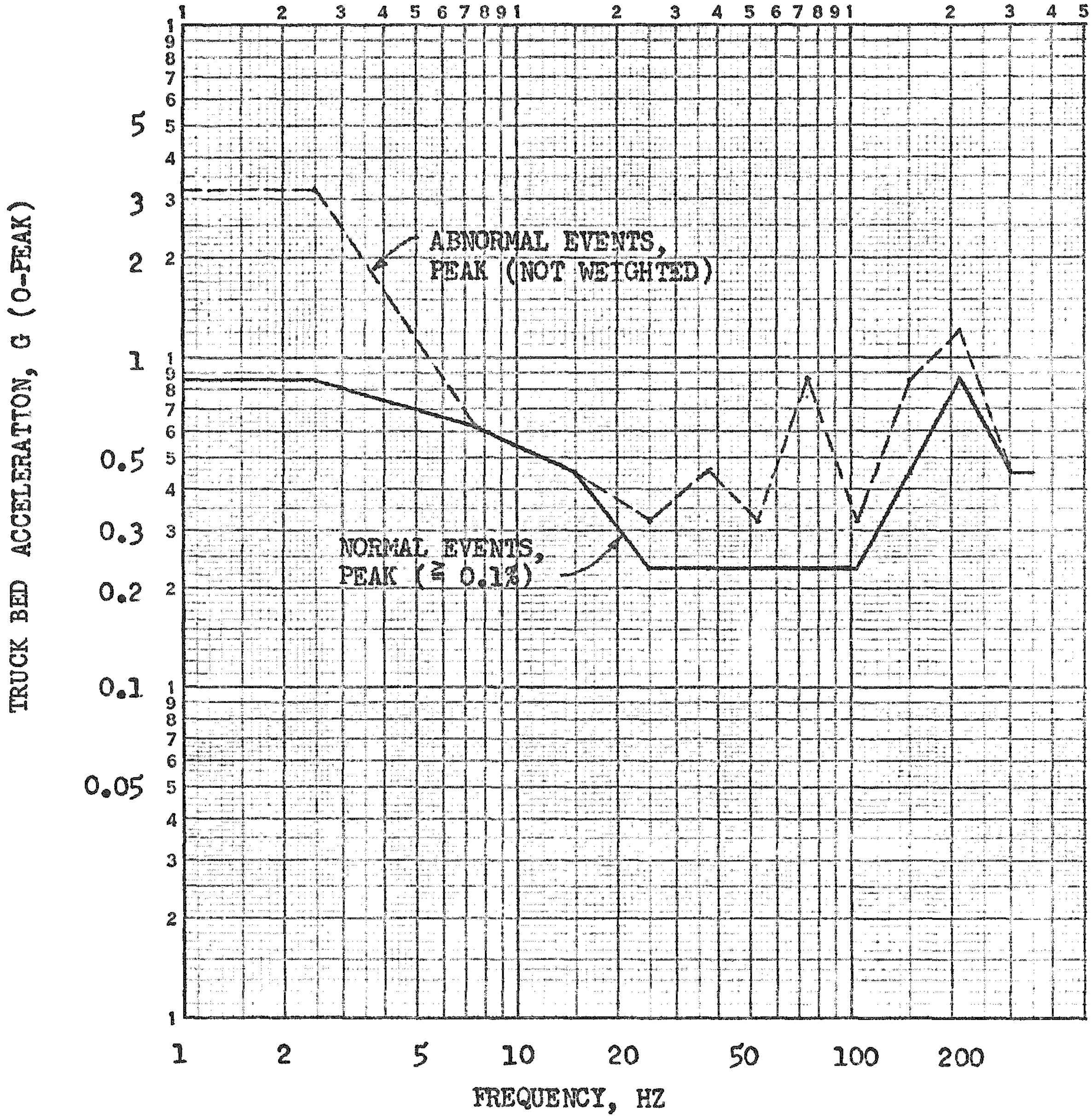


FIGURE 11. COMPARISON OF TRUCK BED PEAK ACCELERATIONS IN VERTICAL AXIS AT CARGO, COMPOSITE FOR NORMAL OR ABNORMAL EVENTS, 2-1/2-TON FLATBED TRUCK, LIGHTLY LOADED (REF. 5)

configuration. In a later report[20], two apparently idential vans were compared, with markedly different acceleration spectra. One van (Van A of the report) obviously had a malfunctioning suspension system, which resulted in reduced shock and vibration levels at the sprung and unsprung mass natural frequencies, but considerably higher vibration levels in the high frequency range. Envelopes of the PSD plots are given in Figure 12, with the dashed curve reflecting the high-frequency transmissibility of the faulty air suspension. The RMS and three-sigma acceleration envelopes of Figure 13 are derived from Figure 12, and show a composite of expected events in long-distance, highway operation.

A recent report by the Hanford Engineering Development Laboratory (HEDL)[22] describes experiments to define the shipping environment of test assemblies in an air suspension van (both tractor and van having tandem-axle air suspensions). About 24,000 pounds of sand-bag ballast were used to bring the load up to nominal weight. Measured at the van floor, three-sigma levels less than 1.05 g (vertical), 0.31 g (transverse lateral), and 1.29 g (longitudinal) were calculated. Several methods of pad-mounting and tie-down of the assembly were investigated during this study. Since the pad, assembly and tie-down act as a spring-mass-damper system, results were found to vary depending upon the natural frequency of this system relative to the dominant frequencies of the trailer acceleration. Important excitation frequencies were noted at 14 Hz (the wheel-hop frequency) and 28 Hz (probably a harmonic of wheel-hop, since the suspension is nonlinear). Data were recorded for a chosen pad and tie-down system consisting of a Pimcore foam pad and nylon tie-down to floor, during transport of the assembly from Argonne National Laboratory to HEDL. During a recorded 8-hour period, the test assembly experienced the following acceleration peaks:

	Number of Peaks Above...			
	0.75 g	1.0 g	1.25 g	1.50 g
Vertical	1031	60	18	2
Lateral	37	16	11	0
Longitudinal	24	11	2	0

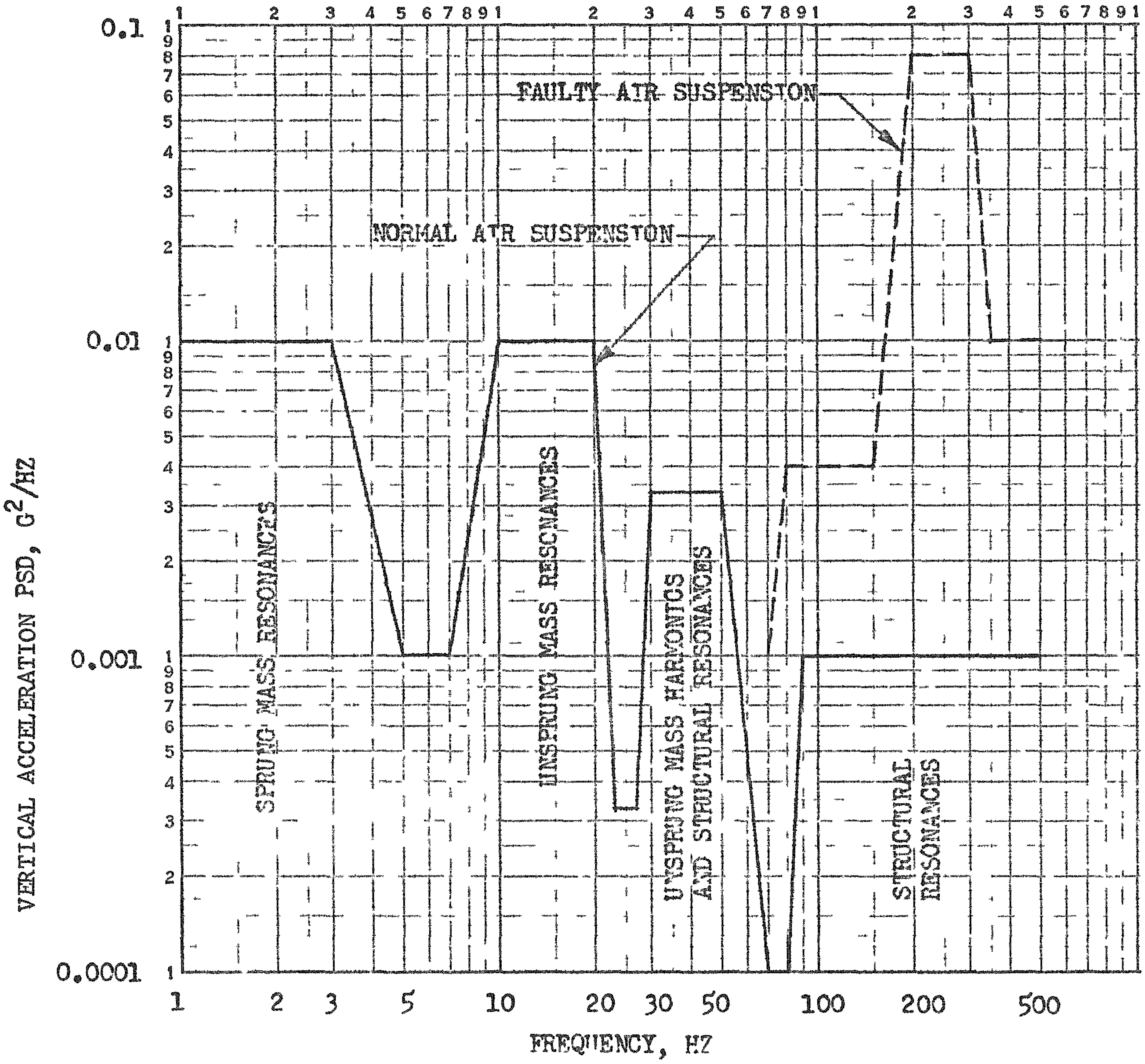


FIGURE 12 . ACCELERATION POWER SPECTRAL DENSITY (PSD) ENVELOPE FOR AIR SUSPENSION TRACTOR AND VAN (TANDEM AXLE), VERTICAL AXIS COMPOSITE FOR ON-HIGHWAY OPERATION, NOMINAL LOAD (REF. 10, 20)

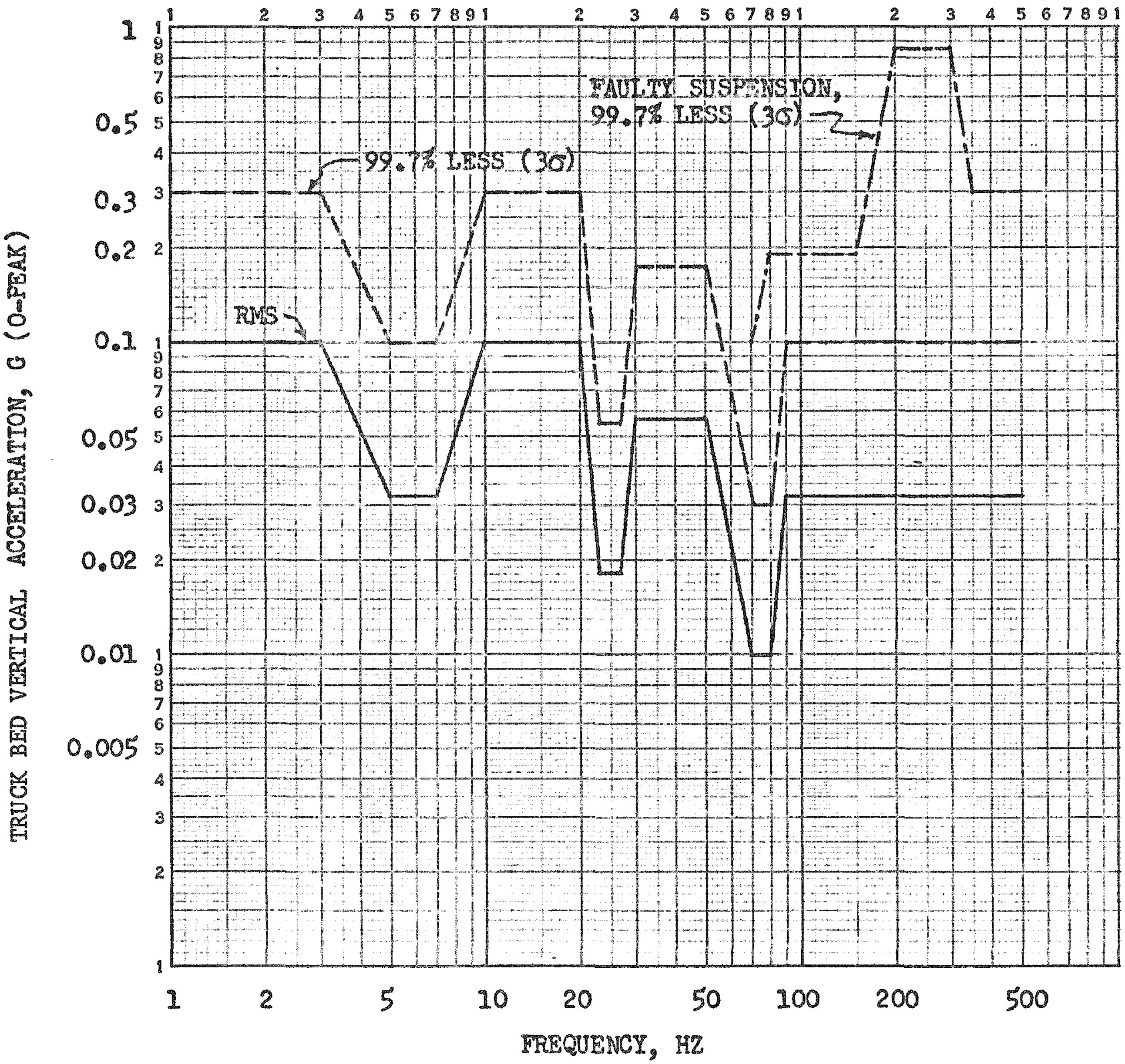


FIGURE 13. ACCELERATION ENVELOPES FOR AIR SUSPENSION TRACTOR AND VAN (TANDEM AXLE) LOADED TO NOMINAL RATING, COMPOSITE FOR EXPECTED EVENTS IN HIGHWAY OPERATION (REF. 10,20)

In terms of "average acceleration" the protected assembly container produced readings not greatly different from the trailer floor:

	Average Acceleration	
	Protected Container	Trailer Floor
Vertical	0.185 g	0.125 g
Lateral	0.121	0.041
Longitudinal	0.100	0.084

* *

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