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Measurement of Lateral and Longitudinal
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John Rodney Antle

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of the requirements for

Masters degree in Packaging



Dr. S. Paul Singh

Major professor

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MEASUREMENT OF LATERAL AND LONGITUDINAL
VIBRATION IN COMMERCIAL TRUCK SHIPMENTS

By

John Rodney Antle

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT

MEASUREMENT OF LATERAL AND LONGITUDINAL VIBRATION IN COMMERCIAL TRUCK SHIPMENTS

By

John Rodney Antle

The increased use of tractor trailers for shipment of packaged products has led packaging engineers to accurately determine the nature of the shipping environment. The purpose of this study was to determine the levels of lateral and longitudinal vibration and to compare these with vertical levels measured in the same truck trailer over various United States Highways.

Four truck trailer shipments, two with light loads and two with heavy loads, were instrumented with accelerometers. Data was recorded on a multichannel FM tape recording unit. From the data acquired, Power Spectral Density plots were developed for various road conditions and then used to compare the vibration levels present at various frequencies. The results showed that below 20 Hz., lateral and longitudinal vibration levels were generally much lower than vertical levels, as expected.

John Rodney Antle

At frequencies above 20 Hz., the lateral and longitudinal levels were similar to the vertical vibration levels. The heavier loaded trucks showed higher lateral and longitudinal levels than the lightly loaded ones. The lateral and longitudinal spectrums followed the vertical spectrums with peaks and valleys located at the same frequencies.

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1.0 INTRODUCTION

In order to design an adequate package system, it is important to know product fragility and the expected distribution environment.

In many cases damage to products can be traced to various vibration forces that originate from transport systems during shipping. It is crucial to know the types and levels of these forces in order to isolate the product from them. Packaging engineers use this information, along with product fragility, to develop new package systems and to evaluate these systems in test labs.

In the United States, shipment by truck is the most common and convenient method of transporting goods over land. Within the last thirty years the percentage of freight shipped by rail has decreased from 47 percent in 1950, to 29 percent in 1980. During the same time period, freight shipped by truck has increased from 26 percent in 1950 to 37 percent in 1980. (National Council of Physical Distribution Management, 1982)

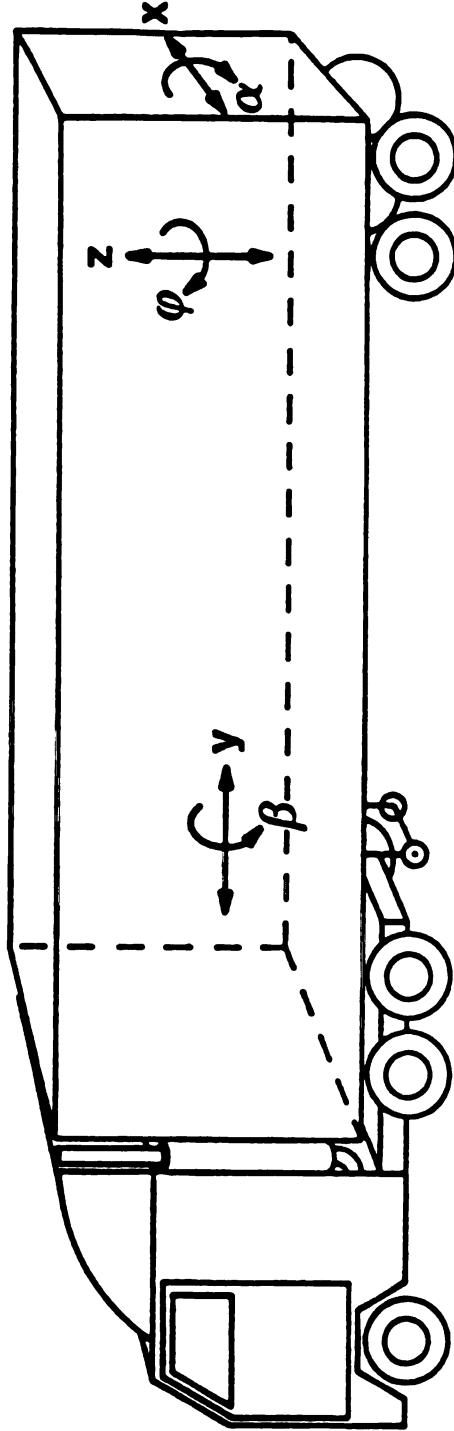
To completely define the movement of a truck trailer as it

travels over the road, six degrees of freedom are needed, Three of these are translations and three are rotations (Figure 1). For truck trailer movement, the rotational movements are normally very small and are therefore ignored in measurement studies. Among the translational movements, vertical vibration is the most severe, followed by lateral and longitudinal vibrations (Sharpe et al, 1974).

Vibration movements in the lateral and longitudinal directions are attributed to:

- 1) Sudden accelerations produced by braking, fast turns, and fast starts.
- 2) Outside weather conditions, especially gusty side winds.
- 3) Uneven road surface profile.
- 4) Variation in road surface between curbside and center, due to weathering, crown, and curbs.
- 5) Localized concentrated loading of product inside of trailer.
- 6) Variation in dynamic response of individual suspension components.
- 7) Unequal air pressure in tires.

Previous studies of vibration in trucks dealt mainly with vertical vibration with only made brief mention of lateral and longitudinal vibrations. The argument for this was that the



3 Translations: x, y, z

3 Rotations: α, β, φ

Figure 1. Degrees of Freedom for a Moving Truck

lateral and longitudinal components of vibration were very low when compared with the vertical component and therefore did not need to be measured. (Sharpe et al, 1974)

Objectives:

The purpose of this study was to measure current lateral and longitudinal vibration levels present in commercial truck-trailer systems traveling over various interstate and intercity roads in the United States. Specifically, the objectives were to:

- 1) Quantify the levels of lateral and longitudinal vibration over various road surfaces.
- 2) Compare the lateral and longitudinal levels with vertical vibration levels measured in the same truck trailer.
- 3) Establish the significance of lateral and longitudinal vibration levels for the truck distribution environment.

2.0 LITERATURE REVIEW

Recent environmental measurement studies that have been done on shock and vibration levels in the truck environment have focused primarily on vertical vibration. Studies which have evaluated lateral and longitudinal vibration in more detail often involve modes of transportation other than truck.

Most of these studies present results in the form of RMS acceleration, or Power Density values versus frequency. The Power Density Spectrums (PDS) are also used in lab testing to simulate the conditions found in the distribution environment (ASTM 4728). The literature review that follows will be presented in chronological order to highlight the development of the subject.

Harris and Credes (1961) present tables listing the normal shock and vibration levels present in truck, tractor-trailer, and train shipments. They also provide basic shock and vibration definitions and concepts as they relate to road and rail vehicles.

The environment on a flatbed tractor-trailer (Foley, 1966) was

measured for an unloaded trailer and one with a 15 ton load. The results were presented in PSD plots for concrete and blacktop roads at speeds of 35 and 50 mph. The vertical vibration was measured at a spot 24 inches behind the location of the 15 ton load.

A study by Schlue (1966), The Dynamic Environment of Spacecraft Surface Transportation, looked at the shock and vibration in vehicles used to transport spacecraft. Measurements were taken in vans driven over smooth, rough, and irregular road surfaces. It was found that:

- 1) Vibration levels at frequencies above 100 Hz were not significant.
- 2) Lateral and longitudinal vibrations were measured, but were not presented in the data because it was found that their levels were less than the levels for vertical vibrations.

Preliminary Measurement and Analysis of the Vibration Environment of Common Motor Carriers (Sharpe et al, 1974) was a study conducted to find the vibration environment of common motor carriers. Some conclusions reached were:

- 1) It is only necessary to measure vertical vibrations because they are the most severe.
- 2) Product testing at various PSD levels for a specified time

period is more desirable than testing at higher levels. These higher levels are equivalent to "worst case conditions" and may be too severe.

Joint Services Highway Shock Index Project (Grier et al, 1975) was a study conducted to obtain data to be used to develop a method to determine the shock index of commercial trucks. This study resulted in:

- 1) A practical method, using planned payload and vehicle axle spring rates, was developed to determine the shock index of commercial trucks.
- 2) During highway travel, vertical accelerations were generally greater than either lateral or longitudinal accelerations and were a major component in potential damage to the cargo.
- 3) The percentage of maximum payload had a much greater influence on the shock index than did vehicle speed or tire pressure.

Caruso and Silver's (1976) study, Advances in Shipping Damage Prevention, compared suspension systems, rear wheel position, road conditions, amount of load, and drivers. Their findings

revealed that:

- 1) PDS levels for frequencies above 50 Hz were insignificant.
- 2) Different suspension types resulted in a different power density at the first peak (about 5 Hz) but beyond the second peak (about 13 Hz), the power density spectra were similar.
- 3) The worst ride occurred on interstate highways at high speeds.
- 4) The worst ride occurred over the rear wheels in a lightly loaded trailer
- 5) The worst rides occurred when single-leaf steel suspension springs were used.
- 6) Different drivers had little effect on the results.

A detailed study of Australian Army trucks (Byrne and Olver, 1976) traveling on second class roads found that:

- 1) Vibrations were highest in the vertical direction, and lowest in the longitudinal direction.

- 2) Longitudinal vibration levels were about $1/3$ to $1/2$, and lateral vibration about $1/2$ to $3/4$ that of vertical rms accelerations.

Magnuson (1977 and 1988) studied the shock and vibration environment for large shipping containers with heavy loads during truck transport. His findings were:

- 1) The vibration observed was random and had a normal Gaussian distribution with respect to acceleration levels.
- 2) The highest vibration levels were generally in the vertical direction but with significant exceptions. These exceptions were usually in the middle frequencies (120 to 240 Hz.) for spring/air suspensions and air suspension systems. Also, below 20 Hz., both the lateral and longitudinal levels were above the vertical acceleration levels in the truck with air suspension.
- 3) Though vertical accelerations were usually the most severe, there were exceptions unique to the vehicle and its operating conditions.
- 4) The type of suspension system caused little difference in vibration amplitude in shipments weighing over 15 tons.

A study entitled Shock and Vibration Environment in a Livestock Trailer (Turczin et al, 1980) was done to determine the shock and vibration environment on the floor of a trailer used to ship cattle. Some findings of this study were:

- 1) Vibration levels greater than 40 Hz were insignificant.
- 2) The highest vibration levels are produced in the vertical direction (peaks to 0.08 g rms).

In 1983, Tevelow summarized many different studies done in the past 20 years. Among his conclusions were:

- 1) The vertical axis almost always has the highest levels of vibration.
- 2) Vibrations in the lateral direction are usually the lowest.
- 3) Vibration levels in the longitudinal axis can be as high or higher than vertical vibration levels, but this usually occurs due to resonant frequencies of the truck body.
- 4) Specific relationships between vertical, lateral, and longitudinal vibration levels are highly dependent upon the vehicle, and external conditions.

Goff et al (1984) studied the effect of different suspension systems on the vibration levels in trucks. Accelerations in the rear of the truck were recorded during half-hour trips on; city and county roads, interstate freeways, bridges, and rail crossings. The three different suspension types were:

- 1) Fixed position air-ride tandem axle trailer.
- 2) Moveable leaf spring tandem axle trailer with the axle at the furthest rear position.
- 3) Same as 2), but the axle was positioned at the furthest front position.

This study found that:

- A) Transient accelerations were much more severe than those generated in steady-state vibration.
- B) Spring leaf suspension with wheels forward resulted in the roughest ride.
- C) Air-ride suspension caused the greatest amplification of vibration inputs by the load.

Goodwin and Holland (1987) studied the distribution environment of two different modes of shipment between Rochester, NY, and Los Angeles, CA. These modes were; Trailer on a Flat Car (TOFC), and Container in a well Car (CIWC). Data was analyzed and presented in terms of PDS.

3.0 EXPERIMENTAL DESIGN

To gather the necessary data for this study four separate truck shipments were monitored to measure the respective vibration levels present in each of the shipping environments. The following four shipments were sponsored by the two major food companies listed.

- 1) Champaign, IL to Lehigh Valley, PA (Kraft Inc.)
- 2) Palmyra, PA to Decatur, GA (Kraft Inc.)
- 3) Beloit, WI to Orangeville, WI (Frito Lay Inc.)
- 4) Killingly, CT to Burlington, VT (Frito Lay Inc.)

To monitor the truck shipments, piezoelectric accelerometers were used, one for lateral motion, one for longitudinal motion, and two for vertical motion. Micro-dot cables were used to connect the accelerometers to Kistler (model 5112) signal conditioners and a Teac XR-310 cassette data recorder was used to record the output from the signal conditioners. The tapes used by the Teac recorder can record more than 5 hours of data each. Figure 2 shows the setup of the environmental measurement system used and Table 1 describes the sensor types and their sensitivity values.

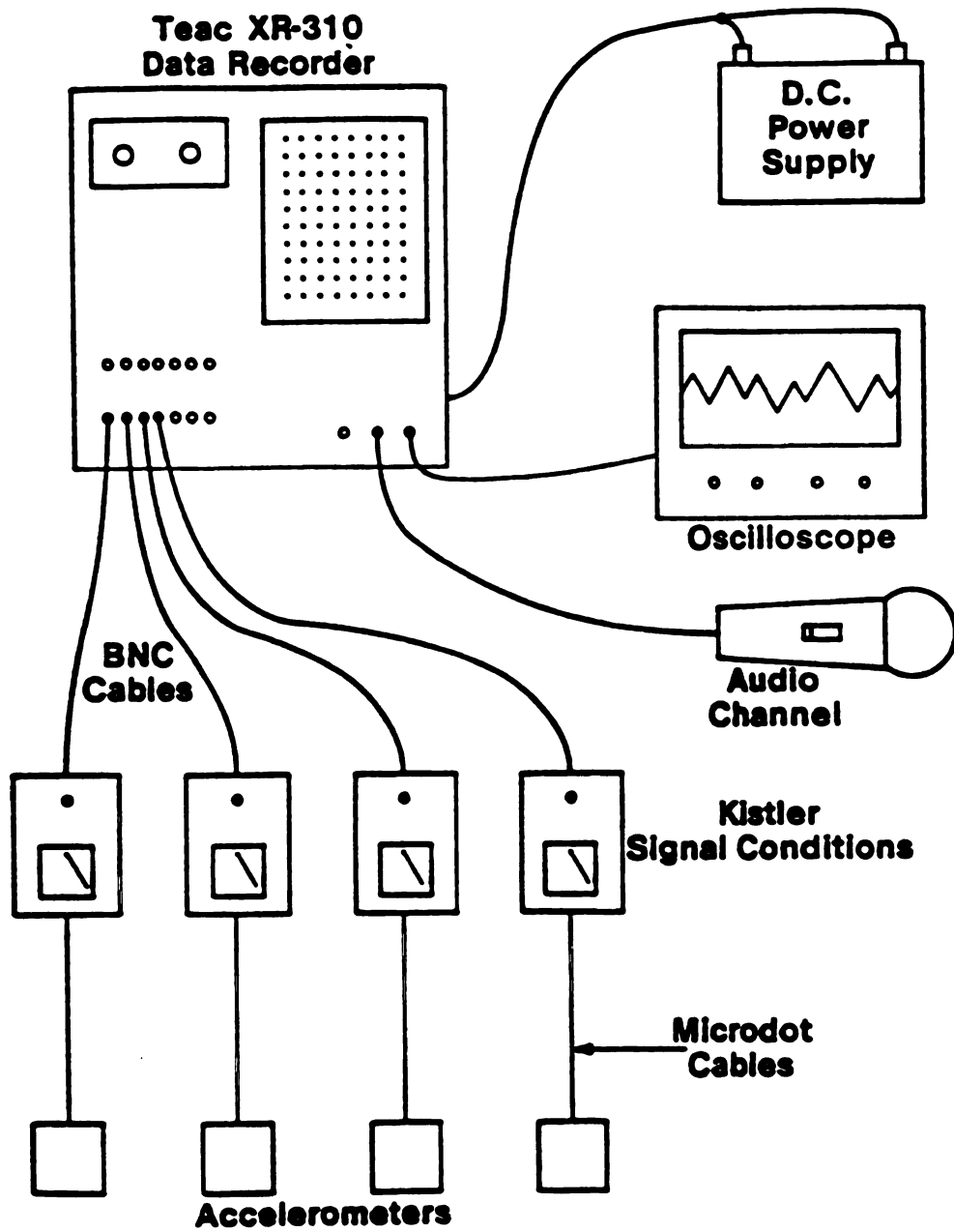


Figure 2. Setup of Data Acquisition System

Table 1. Accelerometer Information

Serial Number	Manufacturer	Model	Sensitivity
14310	PCB	302-A02	10.07 mv/g
14311	PCB	302-A02	9.96 mv/g
14312	PCB	302-A02	10.00 mv/g
14644	PCB	302-A02	10.01 mv/g

SHIPMENT A: Champaign, IL to Lehigh Valley, PA 797 total miles February, 1988.

Champaign to route 32 (near Crawfordsville, IN)	I-74
Route 32 to Lebanon, IN	I-65 S
Lebanon to Indianapolis	I-465 E
Indianapolis to Pennsylvania state line	I-70
Pennsylvania turnpike to Carlisle, PA	I-76
Carlisle to Lehigh Valley, PA	I-81

Trailer: 47 feet x 90 inches (width) x 108 inches (height)
 Tandem axle
 Leaf spring suspension
 Load: pallets of mayonnaise in glass quarts,
 of approximately 40,000 pounds total weight.

Instrumentation: (See Figure 3)

Accelerometer positions:

- 2 vertical (front and rear)
- 1 lateral (left side 12 feet from door, 80 inches above floor)
- 1 longitudinal (right side of nose, 79 inches above floor)

SHIPMENT B: Palmyra, PA to Decatur, GA 716 total miles February, 1988

Palmyra to I-81	US-422
I-81 (near Carlisle) to I-77 S	I-81
I-77 S to Charlotte, NC	I-77 S
Charlotte to Greenville, SC	I-85
Greenville to Decatur, GA	I-85 S

Trailer: 47 feet x 90 inches (width) x 108 inches (height)
 Tandem axle
 Leaf spring suspension
 Load: pallets of crackers, approximately 30,000 pounds total weight

Instrumentation: (See Figure 3)

Accelerometer positions:

- 2 vertical (front and rear)
- 1 lateral (left side 12 feet from door, 80 inches above floor)

1 longitudinal (right side of nose, 79 inches above floor)

SHIPMENT C: Beloit, WI to Orangville, WI October 1988.

Beloit to Madison	I-90 W
Madison to Richland Center	US-14
Richland Center to Dodgeville	US-14
Dodgeville to Avon	US-151
Avon to Monroe	WI-23/WI-11
Monroe to Orangeville	WI-26

Trailer: 47 feet x 96 inches (width) x 162 inches (height);
 drop-frame
 Tandem rear axle on trailer
 Single rear axle on tractor
 Leaf spring suspension
 Load: 1,000 cases of product, break bulk,
 approximately 7,000 pounds

Instrumentation: (See Figure 4)

Accelerometer positions:

2 vertical (front and rear)
 1 lateral (left side, over center line of axles, 60
 inches above floor)
 1 longitudinal (forward face of left wheel well
 cover)

SHIPMENT D: Killingly, CT to Burlington, VT December 1988.

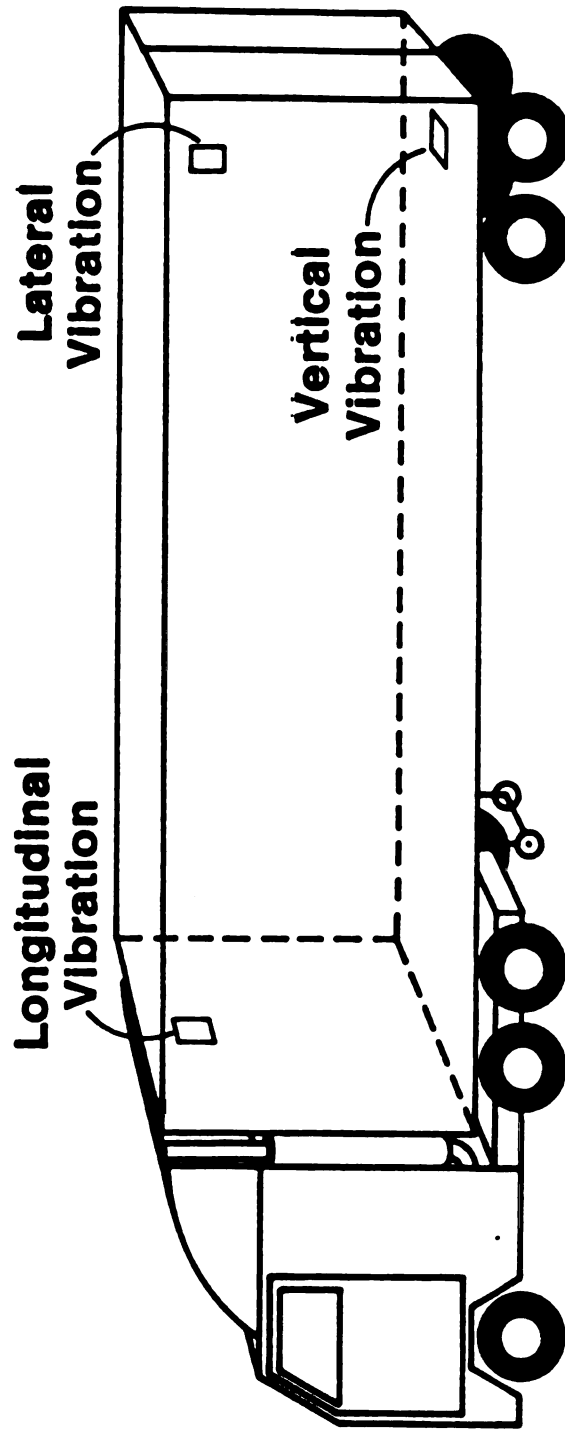
Killingly to Massachusetts turnpike	I-52/I-395
Massachusetts turnpike to Holyoke, MA	I-90
Holyoke to Brattleboro, VT	I-91
Brattleboro to Lebanon, VT	I-91
Lebanon to route 7	I-89
Route 7 to Burlington, VT	I-89

Trailer: 46 feet x 96 inches (width) x 162 inches (height);
 low-frame
 Tandem axle trailer
 Tandem axle tractor
 Load: 1,100 cases of product, break bulk,
 approximately 7,500 pounds

Instrumentation: (See Figure 5)

Accelerometer positions:

- 2 vertical (front and rear)
- 1 lateral (left side, 3 feet forward of rear doors,
60 inches above floor)
- 1 longitudinal (center line of trainer on front
bulkhead, 1 foot above floor)



Accelerometer Locations

Figure 3. Location of Instrumentation for Kraft Shipments

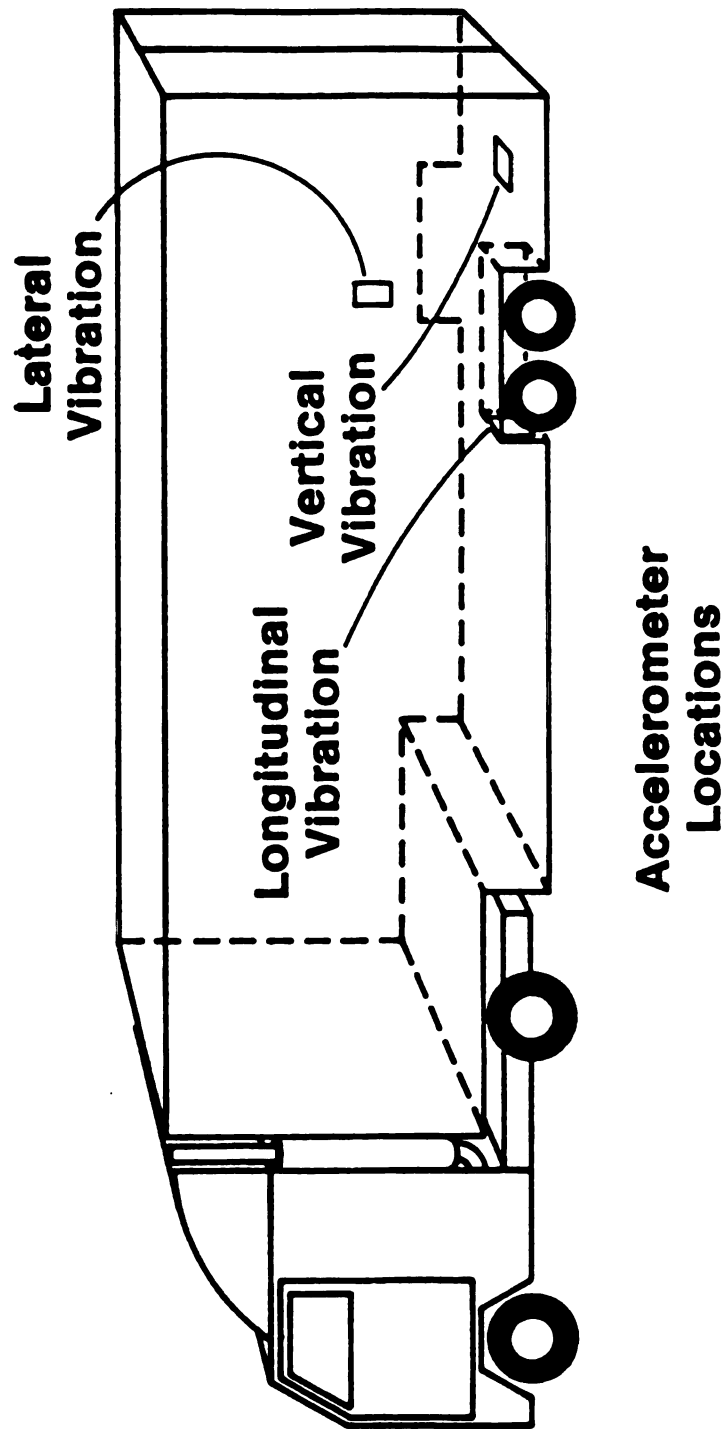


Figure 4. Location of Instrumentation for Wisconsin Frito Lay Shipment

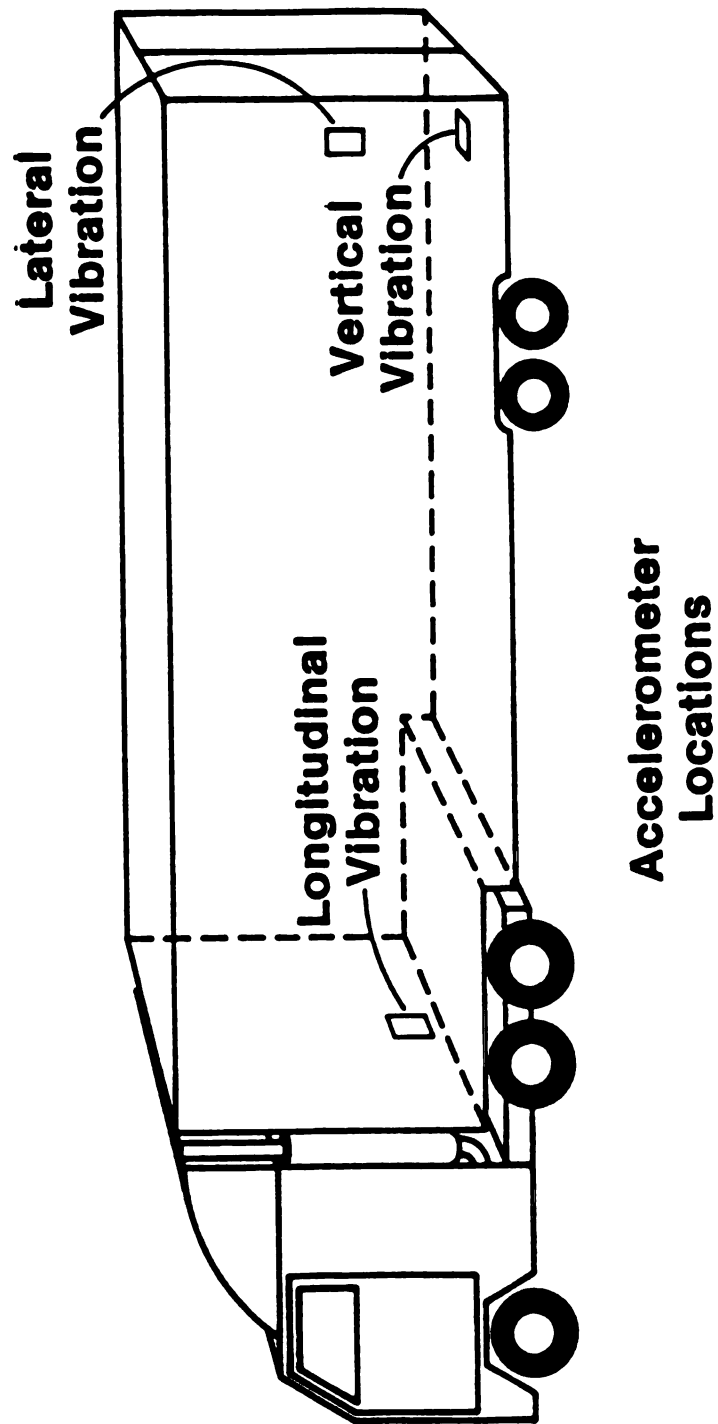


Figure 5. Location of Instrumentation for Vermont Frito Lay Shipment

4.0 DATA AND RESULTS

There are two methodologies of producing simulated varying vibration levels, these are:

- 1) Time Domain
- 2) Frequency Domain

The concept of Time Domain is to exactly reproduce a segment of the distribution system. This method has several shortcomings which limit its application in the area of distribution simulation for the purpose of package development (Singh, Young, 1988). Frequency Domain uses random vibration to simulate the distribution, and is making a significant contribution in this area (Tustin, 1984). The Frequency Demand method was chosen for this study, and a brief description of its workings follows.

The vibration data recorded on tape was analyzed using a Schlumberger 1209 Random Vibration Analyzer/Controller and printed on a Team TP-35 Video Hard Copy Printer. The random vibration analyzer performs a Spectral analysis on the tape recorded data, and produces a Power Density Value for each component frequency of the spectrum. The Power Density Value is calculated as:

$$\text{P.D.} = \frac{\sum_i (\text{RMS})_i^2}{\text{BW}} / N \quad (\text{at a given frequency}) \quad (4.1)$$

where (RMS) _i is the Root Mean Square acceleration value measured in g's at any instant within a band width BW of frequencies and N is the number of instants sampled. The corresponding P.D. is then plotted against the center frequency of the bandwidth. The plot describing the Power Density versus frequency is called the Power Density Spectrum (PDS).

Statistically, the Power Density at a given frequency is the variance about a mean value of zero acceleration. Based on the probabilities associated with Normal Distribution, the acceleration levels associated with any of the component frequencies of the complex wave form can be predicted as follows:

Accelerations within + or - 1 P.D. values occur 68.3 % of the time

Accelerations within + or - 2 P.D. values occur 95.4 % of the time

Accelerations within + or - 3 P.D. values occur 99.7 % of the time

Trailer Vibration:

Figure 6 shows the background noise levels for the recording and analyzing equipment. The levels for this spectrum are no greater than 1×10^{-6} . The spike at 60 Hz. is the result of the line current which operates at 60 cycles per second. Figure 7A shows the vertical and lateral vibration levels in the truck trailer caused by engine vibration and Figure 7B shows engine vibration levels in the longitudinal and vertical directions. The peaks in these spectrums occur at similar frequencies, 32 and 50-60 Hz., and have similar levels.

Tables 2 through 11 show the Power Density values at specific frequencies for the various road conditions that were encountered. Figures 8A through 17B show the Power Density Spectrums that were developed from these same road sections. (Tables 2 through 11 and Figures 6 through 17B are located at the end of this section to preserve continuity) What follows is a brief summary of each Table and corresponding Figures.

It is important to note that the height above the floor of the accelerometers which measure lateral vibrations is extremely important. The top of the trailer will experience more sideways movement than will the floor of the trailer. This fact must be taken into account if comparisons to other studies are made.

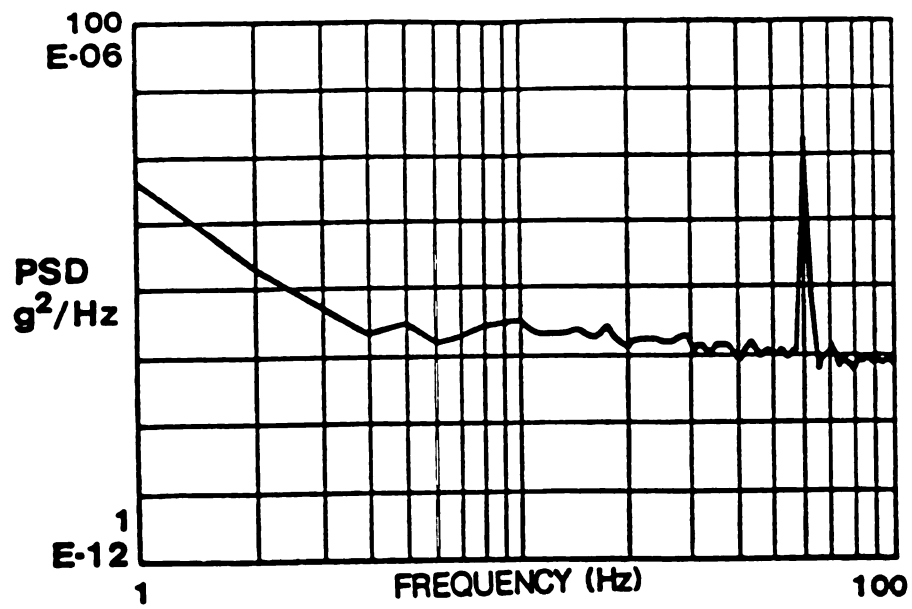


Figure 6. Power Density Spectrum: Background Noise for Analyzing Equipment

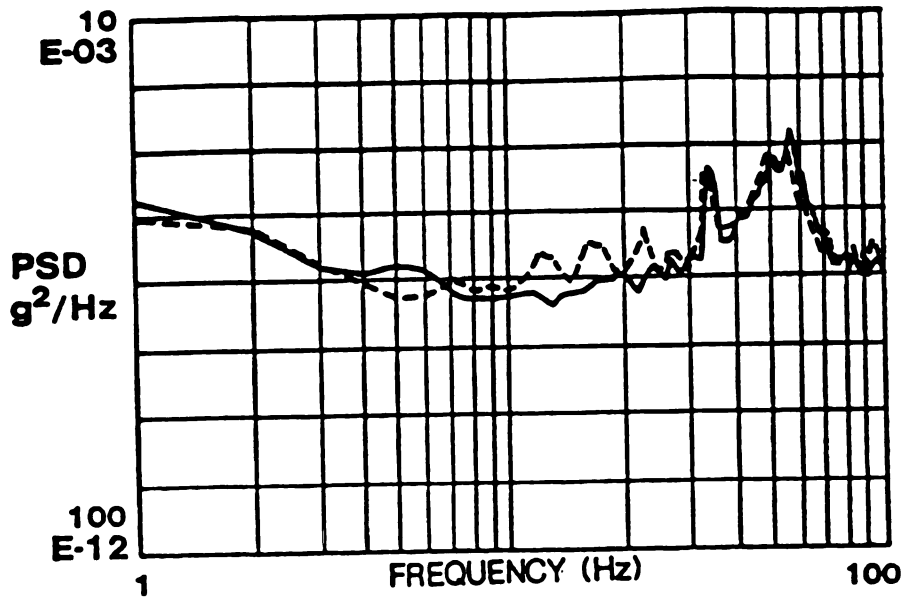


Figure 7A. Power Density Spectrum: Lateral and Vertical Vibrations for Engine Noise, Truck Stationary

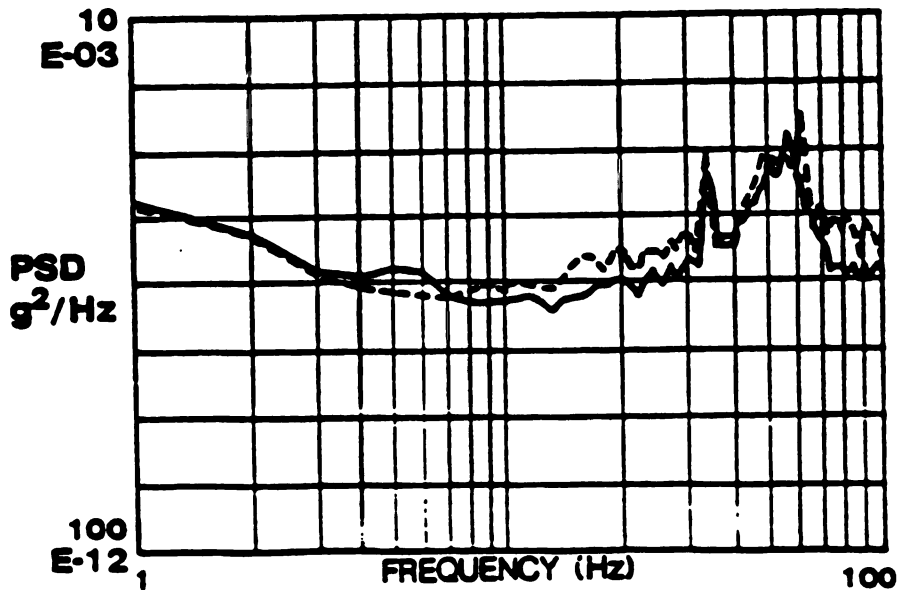


Figure 7B. Power Density Spectrum: Lateral and Vertical Vibrations for Engine Noise, Truck Stationary

Figure 8A shows lateral vibrations and vertical vibrations for a trailer traveling 50 MPH on a smooth concrete expressway with a 7,000 lb. load. The vertical vibration spectrum shows peaks at 4-5 Hz, and again at 15, 20, and 30 Hz. The 4-5 Hz peak corresponds to the suspension system of trailer, while the higher frequency peaks correspond to the trailer structure natural frequencies. The lateral spectrum has peaks at 12, 17, and 28 Hz.

Figure 8B shows longitudinal vibrations and vertical vibrations for the same road segment as above. The longitudinal spectrum shows a long rise from 14 to 20 Hz, and a peak in the 50 Hz. area. These levels are usually 10 times lower than the vertical levels at the same frequency

Figure 9A shows lateral and vertical vibration spectrums for a trailer with a 7,000 lb. load traveling 50 MPH on a smooth concrete road with expansion joints every 18 ft. The vertical spectrum shows a major peak from 3-5 Hz. and another smaller peak from 43-50 Hz. The lateral spectrum has peaks in the 11-12 Hz region, and again at 17-20 Hz. Figure 9B shows longitudinal and vertical spectrums for the same road segment with no peaks in the longitudinal vibrations.

Figure 10A shows lateral and vertical spectrums for a trailer with a 7,500 lb. load traveling on a concrete expressway that is in fair condition. Again, the vertical spectrum shows the first peak to be at the lightly loaded trailer's suspension

natural frequency of 3-4 Hz. Another peak is located in the 15-25 Hz region, which corresponds to the trailer structure natural frequency. Other peaks at 52, 61, and 70 Hz. are the result of the road irregularities being transmitted to the trailer structure. The lateral spectrum shows peaks at 8 Hz., from 14-27 Hz., and from 55 to 70 Hz. In Figure 10B, the longitudinal vibration spectrum indicates a long rise from 13 to 23 Hz. similar to the vertical spectrum. Figure 11A is the spectrum for a lightly loaded truck trailer carrying, 7,500 lbs. and traveling over a smooth blacktop expressway at 50 MPH. The levels are much lower throughout the frequency range, due to the new road surface. The vertical spectrum shows the normal suspension and structure natural frequencies at 3 to 5 Hz. and at 15 and 23 Hz. Other peaks at 40, 50, 60, 70, and 80 Hz. are again most likely the result of engine vibration and the vibration of the trailer body panels. The lateral spectrum shows little excitement until 13 Hz. and again at 23 Hz. and then follows the vertical spectrum in peaks as well as levels.

In Figure 11B, the longitudinal spectrum reveals peaks at 16 and 23 Hz. Here too, the spectrum looks very similar to the vertical spectrum.

Figures 8A through 11B are all for lightly loaded trailers (7,000 to 7,500 lbs.). Because of this, differences in these spectra can largely be attributed to different external

conditions, while similarities are representative of a lightly loaded trailer. The first peak for these four spectra occurs between 4 to 5 Hz. which is the natural frequency for the trailer. Due to the large displacement of the trailer floor, high vibration levels at these frequencies occur and can result in product damage. This occurs in the vertical vibration, (Figures 9A and B) where the vehicle speed and distance between expansion joints matches the 4 Hz. natural frequency of the trailer suspension. A smooth road (Figure 11A and B) results in the vibration levels at these frequencies being lower by a factor of 1,000, as can be seen by comparing the two PSD plots.

For lateral and longitudinal vibrations, the first peak occurs above 10 Hz. and the overall RMS levels are generally much less in the 1 to 10 Hz. range. Beyond 10 Hz. the lateral and longitudinal spectrums look very similar to the vertical spectrum, and the RMS levels are about the same. The exception to this being in Figures 8A and 9A, where a lateral peak at 11 Hz. is substantially greater than the vertical level.

Figure 12A is a spectrum for a heavily loaded truck trailer carrying 45,000 lbs. and traveling at 55 MPH on a newly paved expressway. The first peak is at a lower frequency than previous spectrums, 3 Hz. versus 4 or 5 Hz., because this

trailer has a much heavier load. Again the peak at 8 Hz. is from the trailer structure, and other peaks at 30 Hz. and beyond are again the result of the drive train and frame members. The longitudinal spectrum in Figure 12B shows a peak at 9 Hz. and a substantial peak at 22 Hz. The large peak, at 22 Hz. is the result of the drive train, while the peak at 9 Hz. is also from the trailer structure.

Figures 13A and 13B are spectra for a heavily loaded truck traveling 55 MPH on a rough expressway. The vertical spectrum reveals peaks at 3 Hz. from the suspension of the trailer and another peak at 22 Hz. from the trailer structure. The lateral spectrum shows a peak at 8 Hz. and a large peak at 14 Hz. The longitudinal vibrations in Figure 13B show peaks at 3 and 9 Hz., and a large peak at 16 Hz.

Figure 14A is the spectrum from a heavy loaded truck carrying 45,000 lbs. traveling on a two lane road at 50 MPH. Again, the first peak in the vertical structure is in the 3 to 4 Hz. range, indicating a heavy load, and other peaks at 20 and 30 Hz. are from the trailer structure. The lateral spectrum shows a hump in the 6-8 Hz. band, which can be attributed to sway from the loaded suspension. A second large peak in the 14 to 18 Hz. band is the result of waves in the 2-lane road. Figure 14B for longitudinal vibrations, reveals a peak at 9 Hz. and a larger peak at 20 Hz. The first peak is the trailer structure, while the peak at 20 Hz. is the result of for and aft pitching, due to the variations in the surface of the 2-

lane road.

Figure 15A is a spectrum for a heavily loaded truck carrying 45,000 lbs. and traveling uphill at 40 MPH on a rough expressway. The vertical spectrum again shows the normal peak in the 3 to 4 Hz. band. A second smaller peak is at 8 Hz., while a long peak spans the 15 to 22 Hz. range. A final peak is located at 30 Hz. The spectrum for lateral vibrations shows a large peak at 15 Hz., another peak at 24 Hz., and other peaks at 50, 62, and 80 Hz. In Figure 15B, the spectrum for longitudinal vibration, a hump appears from 3 to 4 Hz., and a peak at 9 Hz. Another peak appears at 20 Hz., which corresponds to pitching from the road conditions.

Figure 16A is spectrum for a heavy truck, 45,000 lbs., on an expressway going downhill with its brakes applied. The spectrum for vertical vibration again shows the familiar suspension hump at 3-4 Hz. and structural peaks at 22 and 30 Hz. The lateral spectrum shows a peak from 7 to 8 Hz., another long peak from 13 to 23 Hz., and a peak at 45 Hz. Figure 16B shows the longitudinal vibrations to peak at 9 Hz. and again from 18 to 23 Hz. These peaks are from similar causes as previously stated.

Figure 17A are the vertical and lateral spectra for a heavily loaded truck traveling at 60 MPH downhill on an expressway. The peaks for the vertical spectrum are located at 3-4 Hz. and at 25 Hz. The spectrum for lateral vibrations contains a peak at 8 Hz., a large peak at 15 Hz., and another peak at 25, 45,

and 80 Hz. Longitudinal vibrations in Figure 17B, show peaks at 9 Hz. and from 20 to 23 Hz.

Figures 12A through 17B are for a heavily loaded truck trailer (40,000 lbs.), so differences in these spectrums versus the spectrums for the lightly loaded truck trailer are expected. The vertical spectrum shows a shift in the first peak from 4-5 Hz. down to 3 Hz. indicating a reduction in natural frequency if the suspension This is caused by the increase in the weight of the load that is being transported. A second peak appears at 8 Hz. and a third in the 20 to 30 Hz. range. The peak which appears at 8 Hz. is probably caused by the lowering of the trailer structure, due to the increased load. The peaks in the 20 to 30 Hz areas fall within the natural frequency of trailer's tires.

The lateral spectra for the heavily loaded truck trailer (Figures 12A through 17A) show two pronounced peaks, at 7-8 Hz., and again from 13 to 23 Hz. The peak at 7-8 Hz., not present in the lighter shipments, has an RMS level equal to the vertical vibration spectrum. The peak in the 13 to 23 Hz range is of greater magnitude than the vertical vibration peak in same frequency range.

The longitudinal vibration spectra, (Figures 12B to 17B) for the heavily loaded truck, also are different than the similar

spectrums developed from the lightly loaded trailer (Figures 8B to 11B). The most noticeable difference in these spectra is the frequency at which the first peak occurs. The hump in the 3-4 Hz. range, which was not present in the Frito Lay shipments, results from the tractor and trailer pitching fore and aft. This motion does not occur in the lighter shipments because spring deflection is small, therefore movement is restricted. Above 10 Hz. the longitudinal spectrum closely follows the vertical spectrum, with levels equal to or slightly above that of the vertical, in the 20 Hz. band.

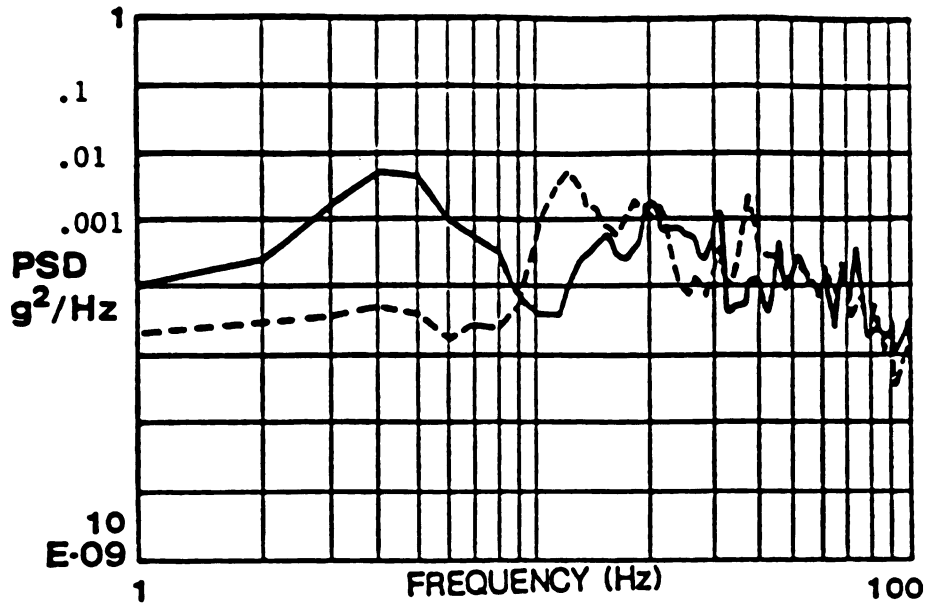


Figure 8A. Power Density Spectrum: Lateral and Vertical Vibrations for Smooth Concrete Expressway 50 MPH (I-90 W Near Beloit, WI); Load: 7,000 lbs.

----- Lateral
 ————— Vertical

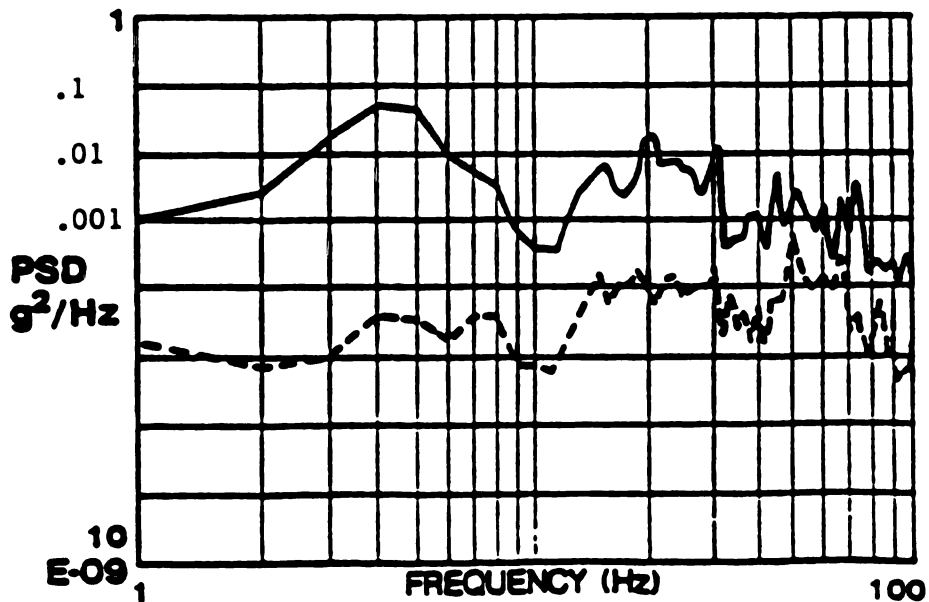


Figure 8B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Smooth Concrete Expressway 50 MPH (I-90 W near Beloit, WI); Load: 7,000 lbs.

----- Longitudinal
 ————— Vertical

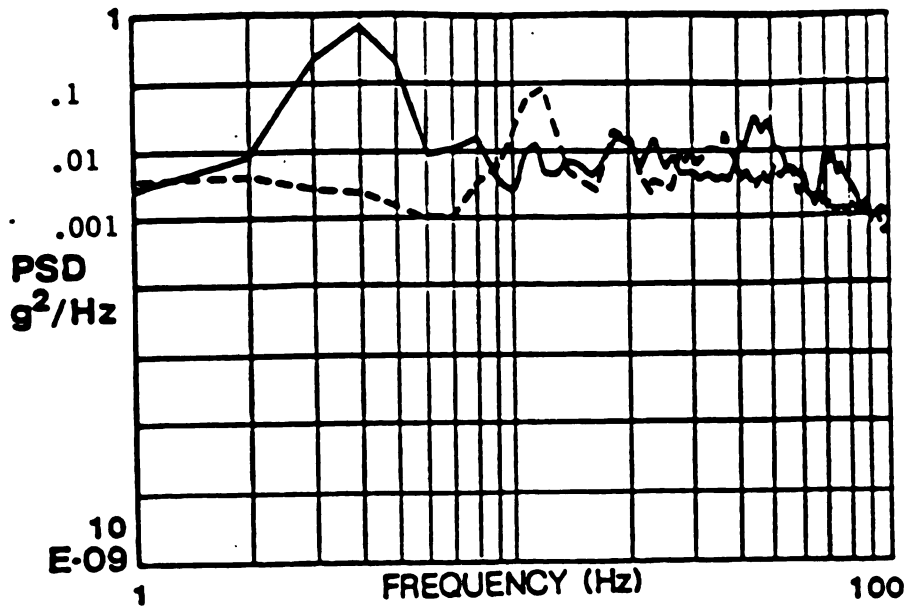


Figure 9A. Power Density Spectrum: Lateral and Vertical Vibrations for Smooth Concrete with Expansion Joints Every 18 Feet, 50 MPH (WI-23); Load: 7.000 lbs.

----- Lateral
 ————— Vertical

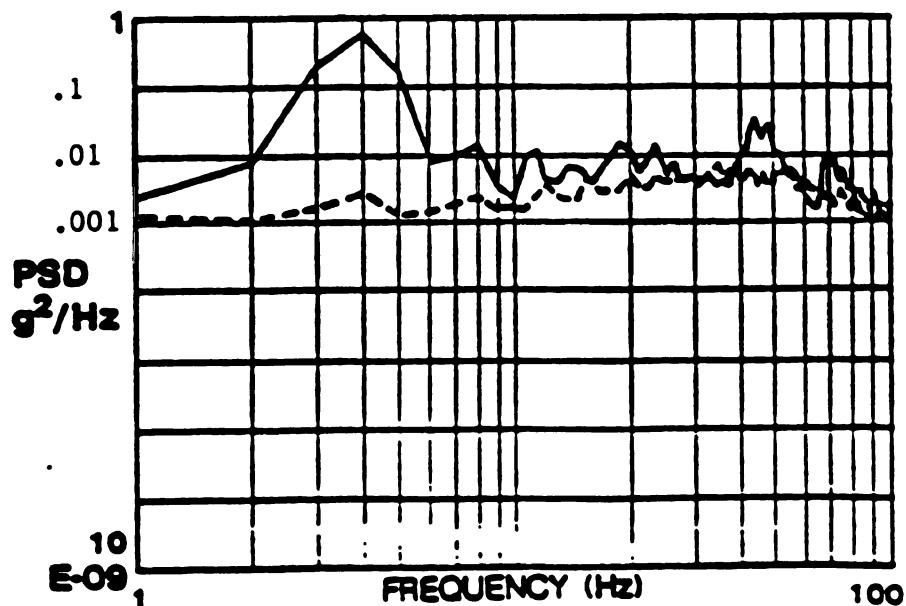


Figure 9B: Power Density Spectrum: Longitudinal and Vertical Vibrations for Smooth Concrete with Expansion Joints Every 18 Feet, 50 MPH (WI-23); Load: 7,000 lbs.

----- Longitudinal
 ————— Vertical

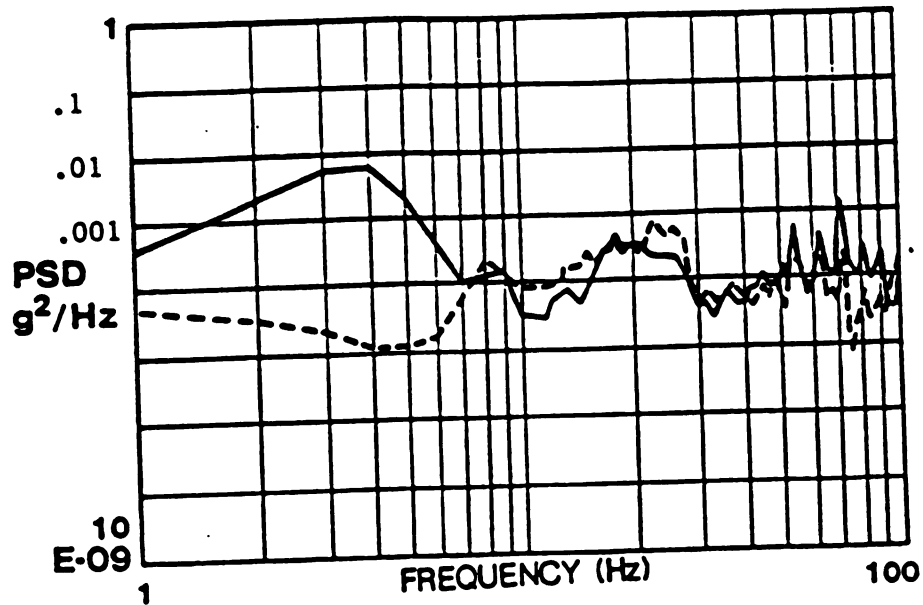


Figure 10A. Power Density Spectrum: Lateral and Vertical Vibrations for Concrete, Fair Condition, 50 MPH (I-90 W Near Killingly, CT); Load: 7.500 lbs.

----- Lateral
 ————— Vertical

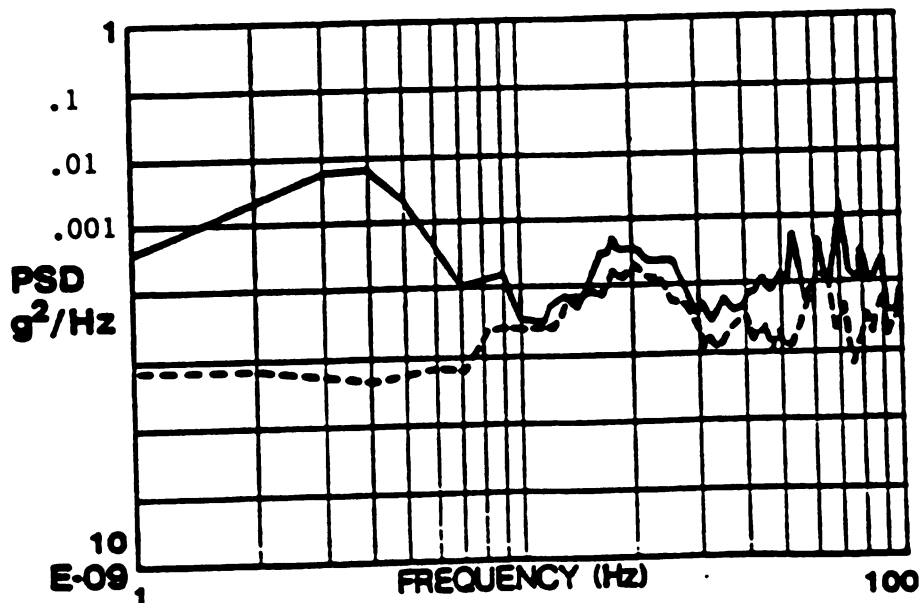


Figure 10B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Concrete, Fair Condition, 50 MPH (I-90 Near Killingly, CT): Load: 7,500 lbs.

----- Longitudinal
 ————— Vertical

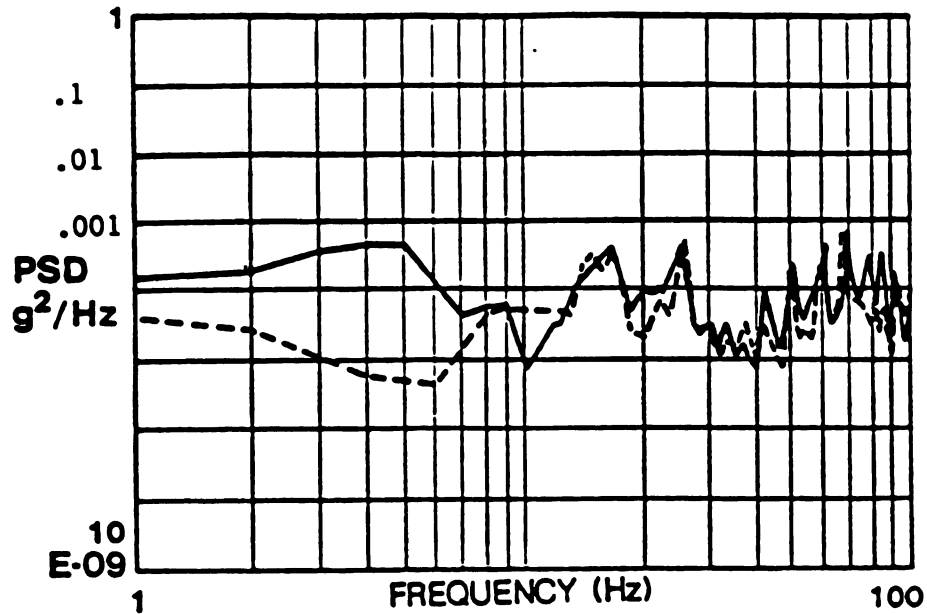


Figure 11A. Power Density Spectrum: Lateral and Vertical Vibrations for Smooth Blacktop Expressway, 50 MPH, (I-91 N near Holyoke, MA); Load: 7,500 lbs.

----- Lateral
 ————— Vertical

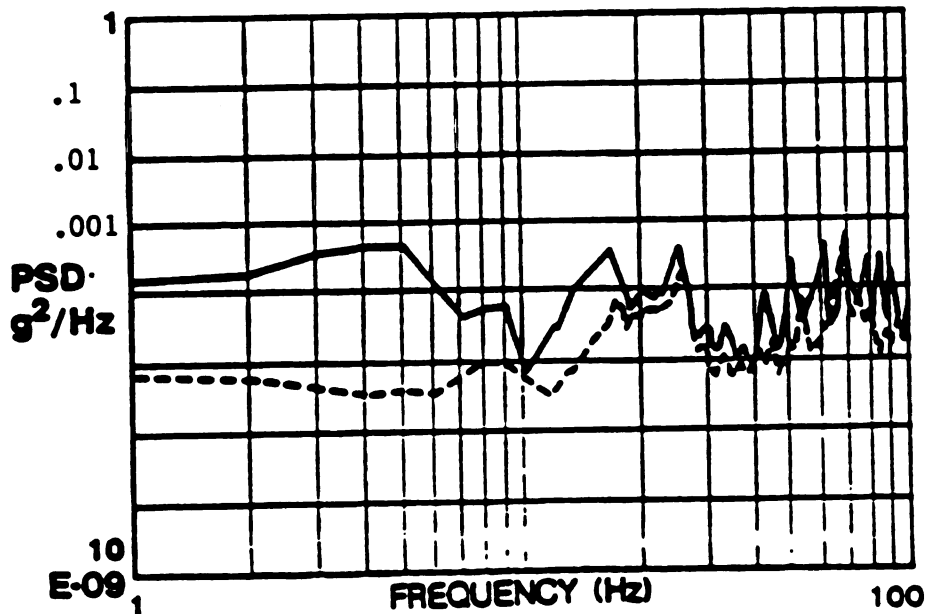


Figure 11B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Smooth Blacktop Expressway, 50 MPH (I-91 N near Holyoke, MA); Load: 7,500 lbs.

----- Longitudinal
 ————— Vertical

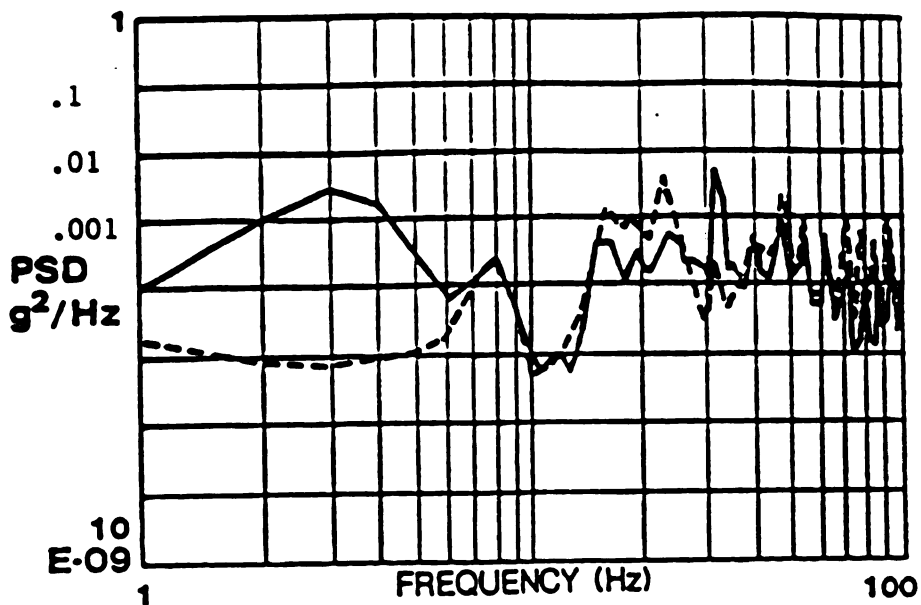


Figure 12A. Power Density Spectrum: Lateral and Vertical Vibrations for Newly Paved Expressway, 55 MPH, (I-74 W, 1 Hour East of Champaign, IL); Load: 40,000 lbs.

----- Lateral
——— Vertical

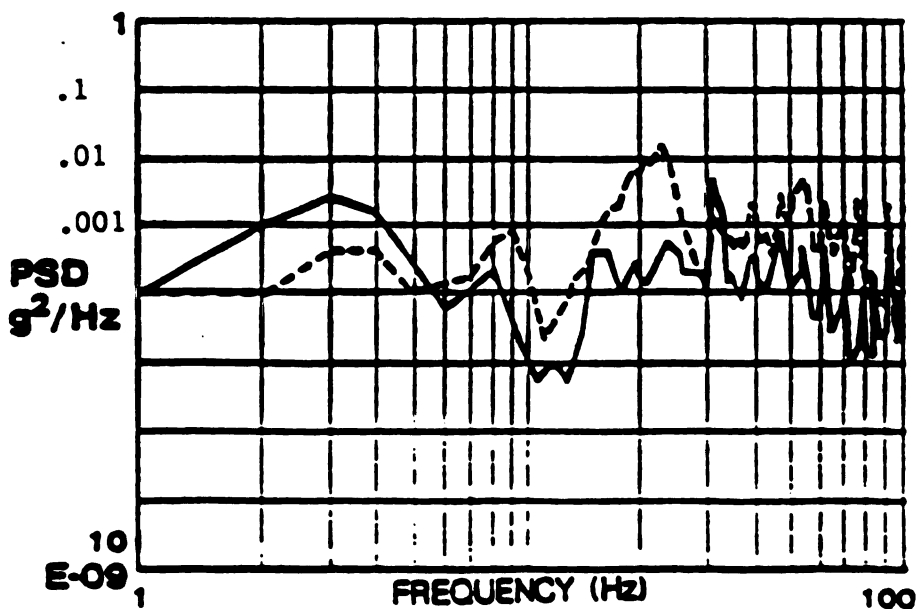


Figure 12B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Newly Paved Expressway, 55 MPH, (I-74 W, 1 Hour East of Champaign, IL); Load: 40,000 lbs.

----- Longitudinal
——— Vertical

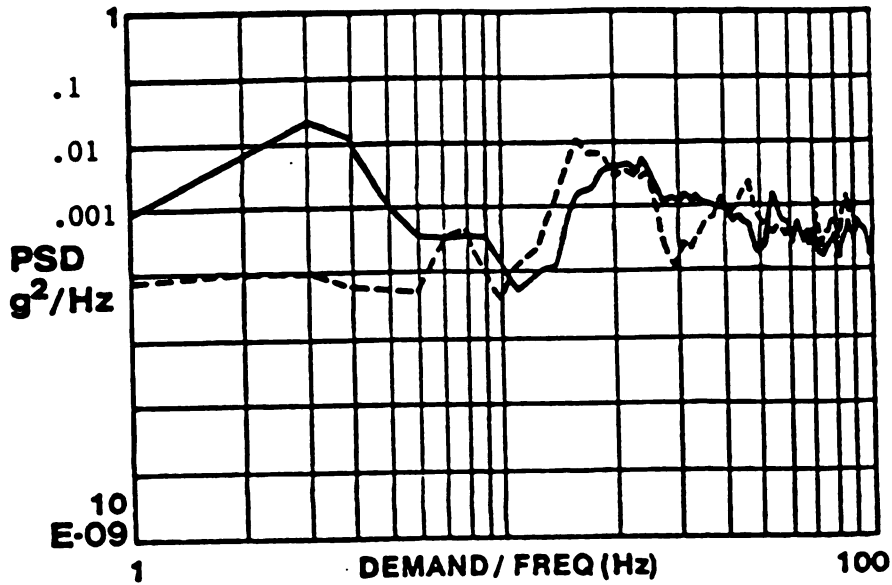


Figure 13A. Power Density Spectrum: Lateral and Vertical Vibrations for Rough Expressway, 55 MPH, (I-74, 90 Miles West of Indianapolis); Load: 40,000 lbs.

----- Lateral
 ————— Vertical

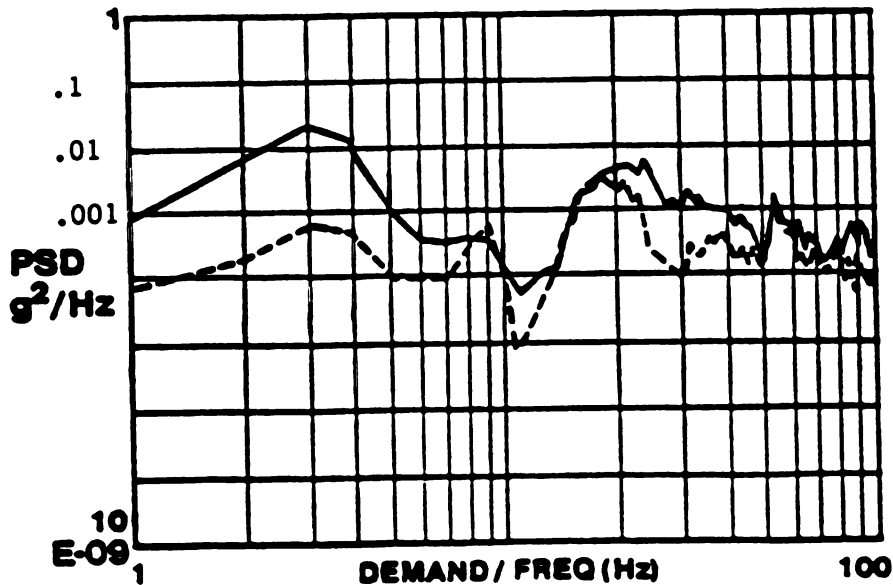


Figure 13B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Rough Expressway, 55 MPH, (I-74, 90 Miles West of Indianapolis); Load: 40,000 lbs.

----- Longitudinal
 ————— Vertical

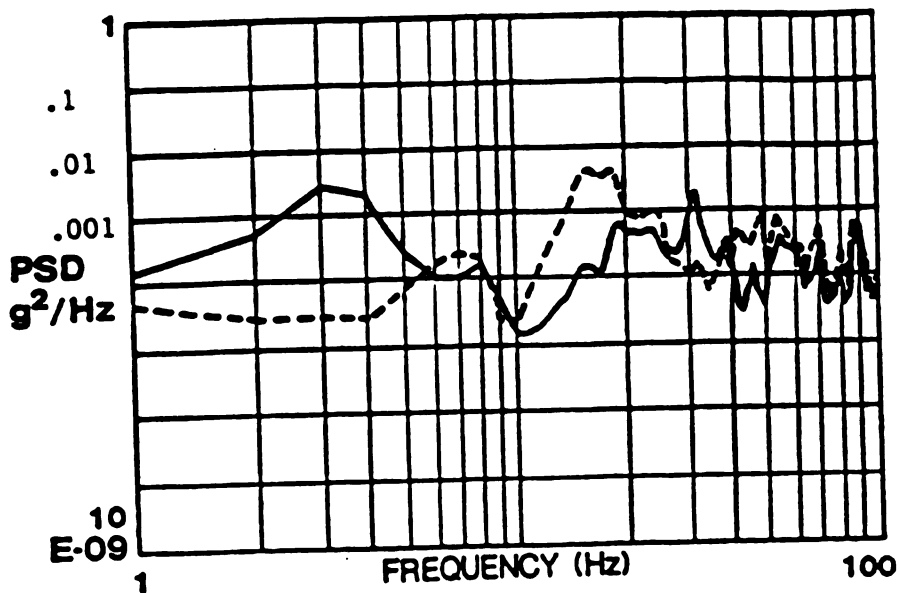


Figure 14A. Power Density Spectrum: Lateral and Vertical Vibrations for Smooth 2-Lane Road, 50 MPH, (Route 32, West of Lebanon, IN); Load: 40,000 lbs.

----- Lateral
 ————— Vertical

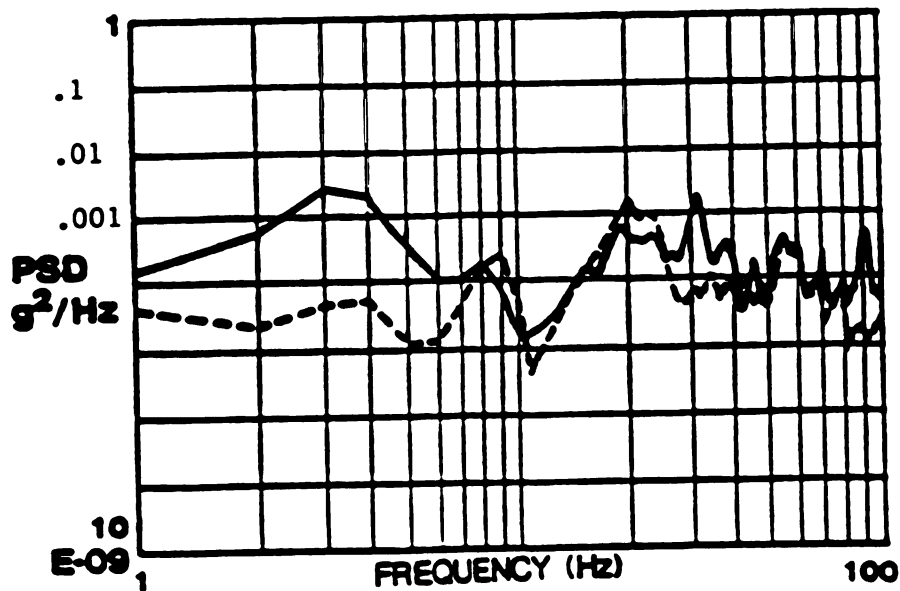


Figure 14B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Smooth 2-Lane Road, 50 MPH, (Route 32, West of Lebanon, IN); Load: 40,000 lbs.

----- Longitudinal
 ————— Vertical

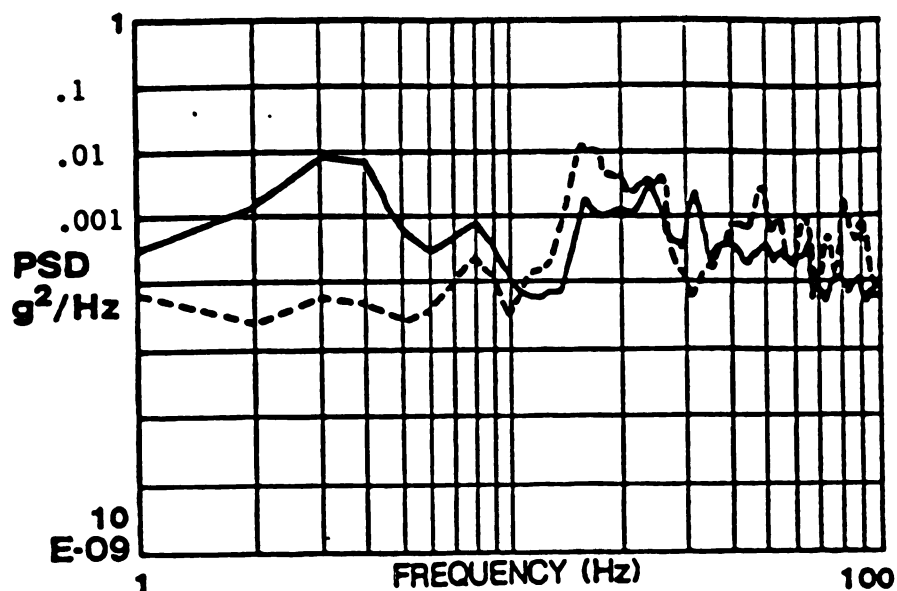


Figure 15A. Power Density Spectrum: Lateral and Vertical Vibrations for Rough Expressway, 40 MPH Uphill, (I-70 E, 30 Miles East of St. Clairsville, OH); Load: 40,000 lbs.

----- Lateral
 ————— Vertical

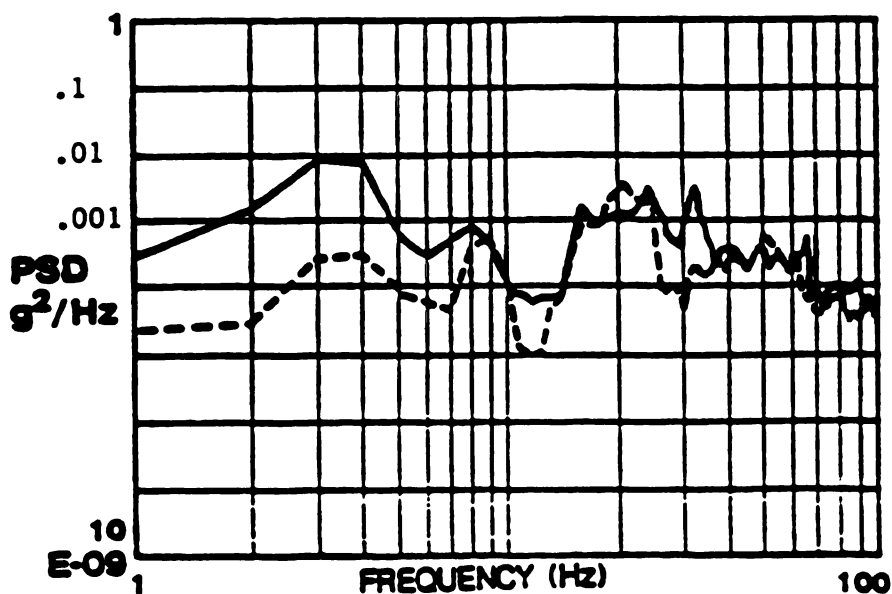


Figure 15B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Rough Expressway, 40 MPH Uphill, (I-70 E, 30 Miles East of St. Clairsville, OH); Load: 40,000 lbs.

----- Longitudinal
 ————— Vertical

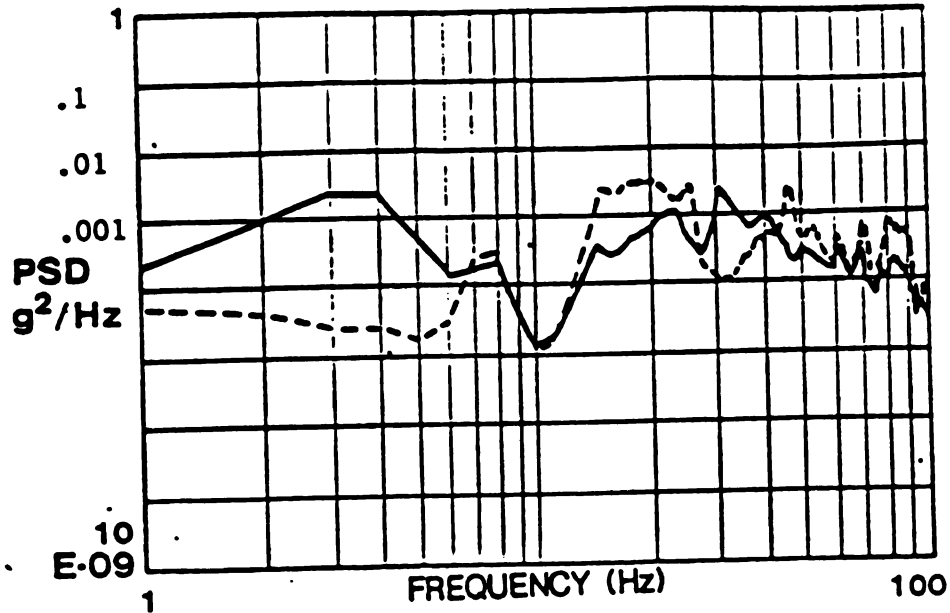


Figure 16A. Power Density Spectrum: Lateral and Vertical Vibrations for Concrete Expressway, 60 MPH, Downhill Braking, (I-70 E, 35 Miles East of St. Clairsville, OH); Load: 40,000 lbs.

----- Lateral
 ————— Vertical

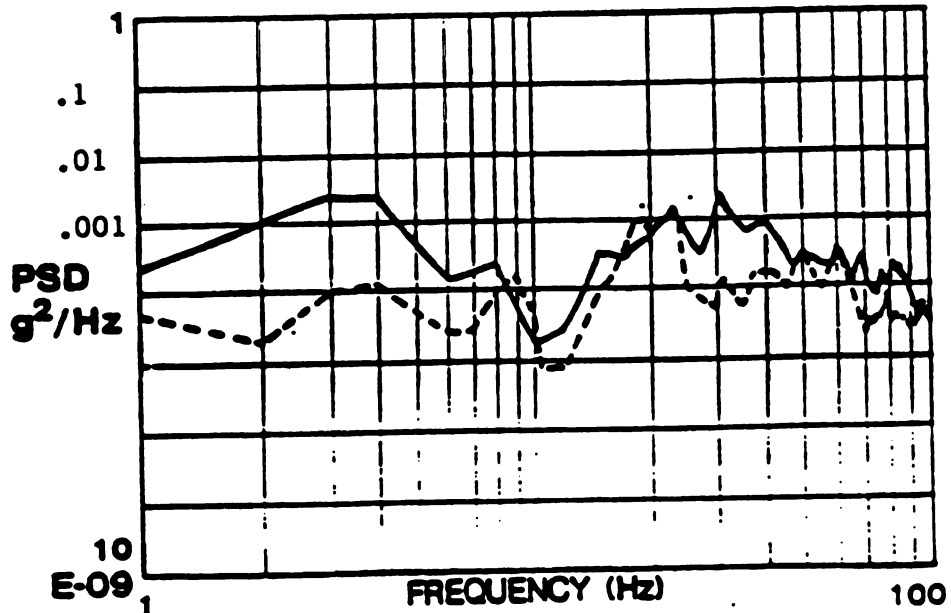


Figure 16B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Concrete Expressway, 60 MPH, Downhill Braking, (I-70 E, 35 Miles East of St. Clairsville, OH); Load: 40,000 lbs.

----- Longitudinal
 ————— Vertical

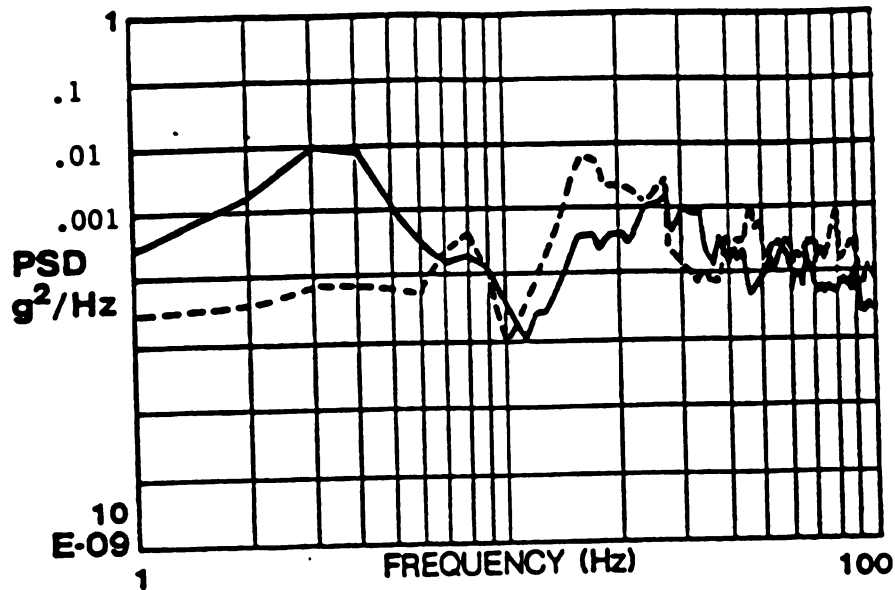


Figure 17A. Power Density Spectrum: Lateral and Vertical Vibrations for Concrete Expressway, 60 MPH, (I-70/I-76, 70 Miles East of Pennsylvania State Line); Load: 40,000 lbs.

----- Lateral
 ————— Vertical

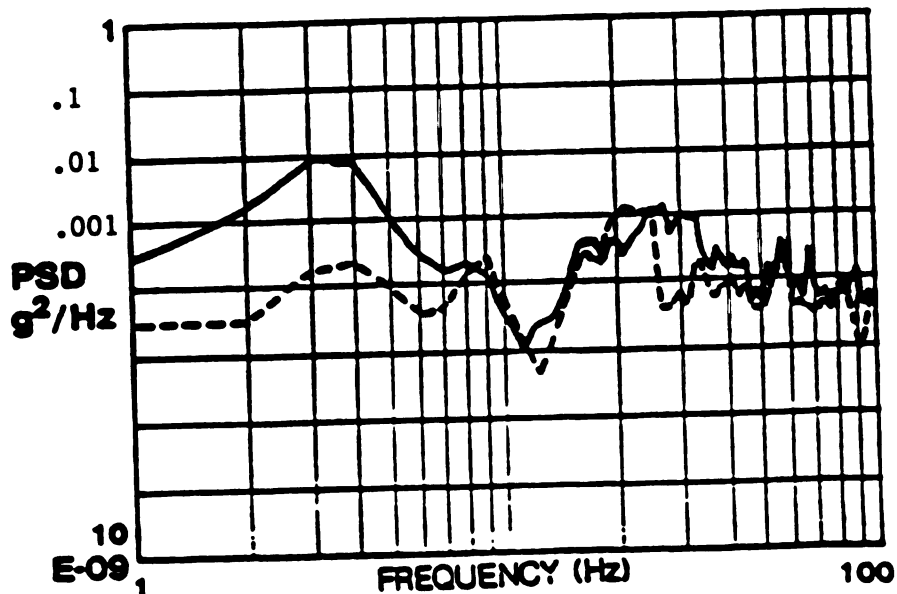


Figure 17B. Power Density Spectrum: Longitudinal and Vertical Vibrations for Concrete Expressway, 60 MPH, (I-70/I-76, 70 Miles East of Pennsylvania State Line); Load: 40,000 lbs.

----- Longitudinal
 ————— Vertical

Table 2. PSD values: Smooth concrete expressway, 50 MPH, (I-90 W near Beloit, WI); Load: 7,000 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	100	20	15	20	15
2	300	30	6	10	2
3	2,000	40	10	2	> 1
4	6,000	53	40	> 1	> 1
5	5,000	40	30	> 1	> 1
6	1,000	15	15	2	2
7	600	23	40	4	7
8	300	20	40	7	13
9	60	53	9	88	15
10	50	200	9	400	18
20	2,000	2,000	100	100	5
30	1,500	400	150	27	10
40	100	300	50	300	50
50	250	300	530	120	212
60	130	100	100	77	77
70	100	60	30	60	30
80	20	50	30	250	150
90	10	10	6	100	60
100	10	13	10	130	100

Table 3. PSD values: Smooth concrete with expansion joints every 20 feet, 50 MPH, (WI-23); Load: 7,000 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	2,500	4,300	1,300	172	52
2	9,000	5,000	1,100	56	12
3	150,000	3,000	1,700	2	1
4	600,000	2,500	3,000	> 1	> 1
5	150,000	1,700	1,300	1	> 1
6	10,000	1,100	1,500	11	15
7	9,000	1,100	1,700	12	19
8	13,000	3,000	2,500	23	19
9	4,000	5,300	1,500	133	38
10	2,500	20,000	1,500	800	60
20	10,000	10,000	4,300	100	43
30	4,300	9,000	4,300	209	100
40	10,000	4,000	3,300	40	33
50	10,000	4,300	4,300	43	43
60	2,500	3,000	3,000	120	120
70	5,300	1,700	2,000	32	38
80	4,000	1,500	1,300	38	33
90	1,500	1,100	2,300	73	153
100	1,300	1,000	1,300	77	100

Table 4. PSD values: Concrete, fair condition, 50 MPH, (I-90 W near Killingly, CT; Load: 7,500 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	400	53	6	13	2
2	1,700	30	6	2	> 1
3	5,300	20	5	> 1	> 1
4	6,000	13	4	> 1	> 1
5	2,300	13	5	> 1	> 1
6	430	17	6	4	1
7	130	53	6	41	3
8	130	200	20	154	15
9	150	130	28	87	19
10	40	90	25	225	63
20	400	300	130	75	33
30	43	60	15	140	35
40	43	60	20	140	47
50	110	40	13	36	12
60	113	113	100	100	89
70	300	100	30	33	10
80	150	53	40	35	27
90	100	40	30	40	30
100	30	40	30	133	100

Table 5. PSD values: Smooth blacktop expressway, 50 MPH, (I-91 N near Holyoke, MA); Load: 7,500 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	130	40	6	31	5
2	150	25	6	17	4
3	300	10	4	3	1
4	500	5	3	1	> 1
5	500	5	4	1	> 1
6	130	4	3	3	3
7	50	13	6	26	12
8	53	40	10	75	19
9	60	53	10	83	17
10	9	50	6	556	67
20	90	15	53	17	59
30	25	15	10	60	40
40	25	10	10	40	40
50	200	200	13	100	7
60	130	300	30	231	23
70	140	100	100	71	71
80	40	30	30	75	75
90	100	30	10	30	10
100	60	100	25	167	42

Table 6. PSD values: Newly paved expressway, 55 MPH, (I-74 W, 1 hour east of Champaign, IL); Load 40,000 lbs.

Freq. (Hz)	Power Density value (*10 -6)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	100	20	11	20	11
2	1,000	10	10	1	1
3	2,500	9	43	> 1	2
4	1,300	10	43	> 1	3
5	250	13	10	5	4
6	63	25	15	40	24
7	130	100	17	77	13
8	20	270	60	1,350	300
9	53	40	90	75	170
10	13	5	17	41	131
20	17	600	600	3,529	3,529
30	1000	60	30	6	3
40	130	300	150	231	115
50	150	110	100	73	67
60	100	100	53	100	53
70	100	600	100	600	100
80	17	40	10	235	59
90	53	90	10	170	19
100	60	170	60	283	100

Table 7. PSD Values: Rough expressway, 55 MPH, (I-74; 90 miles west of Indianapolis, IN); Load: 40,000 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	900	90	60	10	7
2	6,300	100	170	2	3
3	20,000	100	600	> 1	3
4	10,000	60	530	> 1	5
5	1,000	53	100	5	10
6	400	43	10	11	3
7	300	300	100	100	33
8	400	530	300	133	75
9	300	100	600	33	200
10	110	53	100	48	91
20	4,000	3,000	2,000	75	50
30	1,100	150	100	14	9
40	600	1,000	300	167	50
50	250	600	300	240	120
60	300	530	200	177	67
70	300	900	170	300	57
80	200	300	100	150	50
90	600	530	53	88	9
100	200	300	60	150	30

Table 8. PSD Values: Smooth 2-lane road, 50 MPH, (route 32 west of Lebanon, IN); Load: 40,000 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	150	53	43	35	29
2	530	30	25	6	5
3	2,500	33	53	1	2
4	2,000	30	60	2	3
5	200	60	13	30	7
6	100	170	15	170	15
7	100	250	33	250	33
8	150	170	150	113	100
9	53	30	200	57	377
10	15	25	33	167	220
20	600	1000	1,100	167	183
30	1,500	100	53	7	5
40	100	330	60	330	60
50	40	150	90	375	225
60	200	170	170	85	85
70	100	530	30	530	30
80	30	100	17	333	57
90	300	300	17	100	6
100	40	200	20	500	50

Table 9. PSD Values: Rough expressway, 40 MPH uphill, (I-70 E 30 miles east of St. Clairsville, OH); Load: 40,000 lbs.

Freq. (Hz)	Power Density value (*10 -6)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	250	63	25	25	10
2	1,500	27	30	2	2
3	9,000	60	250	> 1	3
4	6,000	53	300	> 1	5
5	600	27	93	5	16
6	300	33	60	11	20
7	400	100	53	25	13
8	900	170	300	19	33
9	400	100	530	25	133
10	100	33	100	33	100
20	1,300	3,000	2,000	231	154
30	600	100	100	17	17
40	300	900	200	300	67
50	300	900	530	300	177
60	200	200	170	100	85
70	100	400	40	400	40
80	60	1,000	100	1,667	167
90	100	300	30	300	30
100	60	90	25	150	42

Table 10. PSD Values: Concrete expressway, 60 MPH, downhill-braking, (I-70 E 35 miles east of St. Clairsville, OH); Load: 40,000 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	250	53	53	21	21
2	1,000	40	20	4	2
3	2,500	27	100	1	4
4	2,500	27	110	1	4
5	530	17	40	3	7
6	150	30	25	20	17
7	170	250	27	147	16
8	250	300	100	120	40
9	60	53	110	88	183
10	17	15	53	88	312
20	600	2,700	600	450	100
30	1,300	100	53	8	4
40	1,000	530	150	53	15
50	250	500	250	200	100
60	170	300	170	176	100
70	250	600	30	240	12
80	100	330	40	330	40
90	100	400	17	400	17
100	30	90	20	300	67

Table 11. PSD Values: Concrete expressway, 60 MPH, (I-70/I-76, 70 miles east of Pennsylvania state line); Load 40,000 lbs.

Freq. (Hz)	Power Density value (*10 ⁻⁶)			Percentage of vertical	
	Vertical	Lateral	Long.	Lateral	long.
1	270	27	33	10	12
2	1,500	40	33	3	2
3	9,500	90	170	> 1	2
4	9,000	90	250	1	3
5	1,000	60	95	6	10
6	300	53	33	18	11
7	150	20	40	13	27
8	170	400	170	235	100
9	130	100	200	77	154
10	40	10	40	25	100
20	400	2,000	1,000	500	250
30	1,000	150	40	15	4
40	170	300	95	176	56
50	90	300	33	333	37
60	100	250	100	250	100
70	90	300	33	333	37
80	40	900	53	2,500	133
90	100	530	10	530	10
100	30	100	10	333	33

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this study:

- 1) Generally, the levels of lateral and longitudinal vibration in commercial truck shipments are much less than the vertical vibrations in the same trailer at frequencies below 10 Hz.
- 2) At frequencies greater than 10 Hz. the lateral and longitudinal spectrums have contours very similar to that of the vertical spectrum.
- 3) The levels of vertical, lateral, and longitudinal vibration at frequencies above 20 Hz. are very similar.
- 4) The displacement at frequencies above 20 Hz., where lateral and longitudinal levels are generally highest, are much less than the displacement at lower frequencies. The RMS displacement necessary to produce 1 g RMS at 3 Hz. is 1.1 inches. The RMS displacement necessary to produce 1 g RMS at 20 Hz. is 0.02 inches.

This number can be calculated by using the following formula:

$$A \text{ (in inches)} = \frac{\text{Acc}}{(2\pi f)^2} * 386.4 \quad (5.1)$$

Where A is the amplitude (displacement), acc is the acceleration, f is the frequency,

From this formula it is evident that for a given acceleration, the amplitude (displacement) is inversely proportional to the square of the frequency. The substantial difference in amplitudes at different frequencies is why low frequency vibrations are more damaging to most products.

Tables 12 and 13 have been included to help summarize this study. They show frequency bands for peaks, RMS acceleration levels, and the causes of the peaks.

Table 12. Summary of a Light Load

	Vertical	Lateral	Longitudinal
Frequency	4-5 Hz.	4-5 Hz.	4-5 Hz.
Average g's (RMS)	0.39 g's	0.028 g's	0.023 g's
Cause of vibration	Suspension	Suspension	Suspension
Frequency	15-25 Hz.	12-20 Hz.	15-25 Hz.
Average g's (RMS)	0.035 g's	0.11 g's	0.033 g's
Cause of vibration	Structure	Structure	Structure
Frequency	33-60 Hz.	40-60 Hz.	50-70 Hz.
Average g's (RMS)	0.04 g's	0.037 g's	0.033 g's
Cause of vibration	Drivetrain	Drivetrain	Drivetrain

Table 13. Summary of a Heavy Load

	Vertical	Lateral	Longitudinal
Frequency	3-4 Hz.	3-4 Hz.	3-4 Hz
Average g's (RMS)	.089 g's	.007 g's	.042 g's
Cause of vibration	Suspension	Suspension	Suspension
Frequency	15-30 Hz.	15-25 Hz.	15-25 Hz.
Average g's (RMS)	.031 g's	.055 g's	.040 g's
Cause of vibration	Structure	Structure	Structure
Frequency	50-70 Hz.	50-70 Hz.	50-70 Hz.
Average g's (RMS)	.014 g's	.041 g's	.018 g's
Cause of vibration	Drivetrain	Drivetrain	Drivetrain

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