This is to certify that the

thesis entitled

A Comparison of Vertical Vibration Levels For
Leaf Spring Versus Air Ride Trailer Suspensions

presented by

Charles David Pierce

has been accepted towards fulfillment
of the requirements for

Masters degree in Packaging

S. Paul Singh
Major professor

Date February 22, 1990

A Comparison of Vertical Vibration Levels For
Leaf Spring Versus Air Ride Trailer Suspensions

By

Charles David Pierce

A Thesis

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Master Of Science

School of Packaging

1990

Abstract

A Comparison of Vertical Vibration Levels For Leaf Spring Versus Air Ride Trailer Suspensions

By

Charles David Pierce

Packaging engineers need to accurately determine the forces present in the shipping environment in order to protect packaged goods. The purpose of this study was to determine the vertical vibration levels measured in three seperate suspension systems; conventional air-ride, damaged air-ride, and conventional leaf-spring

Six tractor trailer shipments with different ladings were monitored over the same shipping route. Power Density plots were developed for various road conditions and suspension type. These in turn were used to compare the vibration levels present at various frequencies.

Conclusions from this study are that air-ride suspension when maintained gives lower Power Density (P.D.) levels on all road surfaces. A damaged air-ride suspension and leaf spring suspension are very similar in response frequencies. The damaged air-ride gives higher P.D.levels at low frequency.

Acknowledgements

I would like to express my sincere appreciation to my major professor Dr. S. Paul Singh for his guidance and everlasting friendship. I also would like to thank the other members of my committee, Dr. Gary J. Burgess, Dr. Julian J. Lee, and Dr. George E. Mase.

I also thank Unisys for the support they provided during this study, Wendy Aquilina for providing all her help and Jorge Marcondes and John Antle for all the help they gave me in the past year.

Finally, I would like to thank all the faculty and students at the School of Packaging and Michigan State University who have helped to keep me sane over the last year.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 Introduction

To effectively design a package/product system, it is critical to know the product fragility and expected forces in the distribution environment. Product damage can frequently be traced to various vibration forces that originate in various transport systems. It is important to measure the levels and types of forces present in a company's specific distribution environment. Engineers can use this information in conjunction with the fragility of a product to effectively develop a package system which will protect the product from damage. This information can also be used to evaluate packages in simulated lab shipment tests.

Shipment by truck is the most common method, in the United States, for transporting goods over land. Within thirty years, the percentage of freight shipped by truck has increased from 26 percent in 1950 to 37 percent in 1980 (National Council of Physical Distribution Management, 1982). The origin of shock and vibration comes from two sources in a truck/trailer system.

1) External sources, such as road or surface irregularities, braking, and forward acceleration.

2) Internal sources due to the vehicle itself such as engine vibration, drive mechanisms, and wheel imbalance (Harris, 1961).

The magnitude of these shocks and vibrations transmitted to the product are in turn affected by the type of suspension system which supports the truck/trailer system. It is commonly thought that an air-ride suspension will give a much smoother ride than leaf spring, therefore protecting products more efficiently. However, air ride suspensions are much more expensive, estimated to cost an average of $0.30 more per mile (Kelly, 1989). These systems also are known to "break down" frequently, which could result in severe vibration levels.

The added cost of an air ride suspension system needs to be justified by a product's need for a lower vibration level and also must be shown to function better than that of leaf spring for given distribution routes.

OBJECTIVES

The purpose of this study was to measure current vertical vibration levels present in commercial truck-trailer systems for each of the three suspension systems;

1) Conventional air-ride (maintained properly)
2) Damaged air-ride (air bled out of the system)
3) Conventional leaf spring.

These levels were measured as a function of lading weight and road surface quality. Specifically, the objectives were to:

1) Quantify the levels of vertical vibration levels for the above three suspension systems over various road surfaces and two different trailer lading weights.

3) Compare the vertical vibration levels measured for each truck-trailer suspension over the same road surface and lading weight.

4) Establish the advantages and disadvantages of air-ride suspension versus a leaf-spring suspension.

2.0 Literature Review

Recent environmental studies that have evaluated shock and vibration levels in a truck distribution environment have dealt mainly with leaf spring suspensions. A literature review reveals no prior study, explaining the vibration levels of an air-ride suspension which has been damaged or poorly maintained.

Most of these studies present results in the form of RMS acceleration level, or Power Density (P.D.) values versus Frequency. These concepts are explained in more detail in Appendix A. The literature review that follows will be presented in a chronological order to highlight the development which has taken place on this subject.

Harris and Crede (1961) presented basic definitions and concepts for shock and vibration concerning road and rail vehicles. They also presented tables of typical shock and vibration levels present in train, truck, and tractor-trailer combinations under normal operating conditions.

The Environment Experienced by Cargo on a Flatbed Tractor-Trailer Combination (Foley, 1966) was performed to gather and analyze data for heavy load shipments. Tests were performed on an unloaded trailer and one with a 15 ton load. The results were presented in PD Spectrums for concrete and blacktop highways at speeds of 35 and 50 miles per hour.

The Dynamic Environment of Spacecraft Surface Transportation, a study performed by Schlue (1966), looked at shock and vibration characteristics to be used in designing transportation vehicles for spacecraft. Comparisons were made for vans on three trips over rough roads, irregular roads and smooth highways. The study concluded that air-ride suspension systems are adequate for spacecraft shipment.

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

1) Only vertical vibrations need to be measured because they are the most severe.

2) Product testing should be performed at various P.D. levels for specified periods of time. Enveloping P.D.

data was equivalent to selecting the worst case condition and could result in a severe test requirement.

Caruso and Silver's (1976) study, Advances in Shipping Damage Prevention, compared cargo losses in tractor-trailer combinations with similar suspension systems but different; rear wheel position, degrees of loading, road types, and drivers. The conclusions which they arrived at were:

1) P.D. levels for frequencies above 50 Hz. were not significant.

2) Similar suspension systems on different trailers produced similar responses.

3) Different trailer 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 levels were similar.

4) The worst ride occured on interstate highways at high speeds.

5) Single-leaf steel suspension springs produce the worst ride conditions.

6) The worst ride occured in a lightly loaded trailer in which the load was placed over the rear wheels.

7) Different drivers had little effect on the results obtained.

Shock and vibration environment studies (Magnuson, 1977 and 1978) were performed on large shipping containers with heavy cargo during truck transportation. The results showed that the vibration history was random and had a normal Gaussian distribution with respect to acceleration levels. It also concluded shipments weighing more than 15 tons showed little difference in vibration amplitude regardless of suspension type.

Tevelow, in 1983, summerized twelve previous reports on trucks. He used this to characterize the military logistical transportation vibration environment with respect to the shipment of fuzes using various types of vehicles (truck, sea, rail, and air). Among his conclusions were:

1) The vertical axes almost always has the highest levels of vibration.

2) Specific relationships between vertical, lateral, and longitudinal vibration levels are highly dependent upon the vehicle, suspension, and external conditions.

Goff et al (1984) reported vertical disturbances caused by large amplitude transients. Accelerometers were mounted on both the truckbed and on packaged products. This was used to monitor the degree of vibration magnification. Data was taken from a half-hour test over city and country roads, interstate expressways, bridges, and railroad crossings. Only accelerations in the rearmost portion of the trailer were recorded. Three different suspension systems were studied:

a) Moveable leaf spring tandem axle trailer with the axle at the rear most position.

b) Same axle as a), but with axle in forward position.

c) Fixed position air-ride tandem axle trailer.

This study found that:

1) Transient accelerations were much more severe than those generated in steady-state vibration.

2) Spring leaf suspension with wheels forward resulted in the roughest ride.

3) Air-ride suspension caused the greatest amplification of vibration inputs by the load.

4) The air ride suspension bed had the lowest levels.

American President Companies (1986) performed a study comparing double-stack/truck/vessel ride characteristics. Accelerations were recorded while the products were transported by ship, APL stack train, and truck trailer. Instruments were positioned so that accelerations of each container and product could be recorded.

This study showed that vessel transportation generated the lowest acceleration levels during the entire trip. The double-stack intermodal cargo transportation system proved to be the smoothest of available inland transportation modes. Truck shipments remained the highest vibration environment among the tested modes of transportation.

Goodwin and Holland (1987) studied the rail distribution environment from Rochester, NY, to Los Angeles, CA, via Chicago, IL. They took into consideration two modes of shipment, Trailer on a Flat Car (TOFC) and Container in a Well Car (CIWC). A change of mode from TOFC to CIWC was made in Chicago. Power Density spectrums were developed for each of the three axes. Percentages of shocks measured were then reported for similar loading in both modes and four directions, longitudinal, lateral and two vertical axis (rear and front). This study was aimed at expanding the information base on LTL shipments, specifically on low, medium and high natural frequency packages. A knowledge of the effect of truck vibration on the different dynamic characteristics of packages is crucial for the planning of LTL shipments, specifically on the stowage of packages.

Goff et al (1988) continued to study transient events for trucks having three different suspension types, traveling over "bumpy" roads. The conclusions were:

1) The lading always amplified the product acceleration over that of the trailer bed.

2) An air-ride suspnsion system did not perform significantly better than a spring leaf suspension with the wheels moved all the way to the rear of the trailer, when comparing the largest transient events.

3) The most severe impacts were generated when the rear spring leaf tandem is moved all of the way forward.

Dynamic Analysis of a Less Than Truckload Shipment (Marcondes, 1988), studied the response of the truckbed and instrumented packages to a given vibration input. The input was a result of six independent vibration actuators positioned under the truck wheels to vibrate the truck and simulate road conditions. The conclusions reached were:

1) For the same input at the axles, the response at the rear of the trailer is 50% larger than that at the front.

2) Roadside or curbside locations input little difference along the same axle.

3) The front axle and the fifth wheel also contribute with the input to the truckbed. The front axle contributes about 20% of the vibration input to the rear truckbed. The fifth wheel contributes about 30%. The rear axle contributes the remaining 50%.

Measurement of Lateral and Longitudinal Vibration in Commercial Truck Shipments (Antle, 1989) was a study performed to determine the significance of lateral and longitudinal vibrations, in comparison to vertical vibration levels, in truck shipments. These tests were conducted on a variety of road surfaces and at various speeds. The conclusions reached were:

1) The levels of lateral and longitudinal vibration 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.

3.0 EXPERIMENTAL DESIGN

To gather the data necessary for this study six different truck shipments were monitored. These shipments were conducted in the Lansing, Michigan area covering the same route as outlined below.

Section 1 - School of Packaging to Trowbridge Road

Speed limit:	25/35 mph
Pavement:	Asphalt with cracks
Distance:	0.9 miles

Section 2 - Trowbridge Road, enter I-496, exit at Grand Ave.

Speed limit:	55 mph
Pavement:	Asphalt
	Concrete with joints, grooved pavement
Distance:	2.4 miles

Section 3 - Washington to Mt. Hope Rd.

Speed limit:	30 mph

Pavement:	Asphalt with cracks
Distance:	1.0 miles

Section 4 - Mt. Hope to Waverly

Speed limit:	30 mph
Pavement:	Asphalt with a few cracks
Distance:	2.8 miles

Section 5 - Waverly to US-27

Speed limit:	35 mph
Pavement:	Concrete with joints
Distance:	0.4 miles

Section 6 - US-27 to Packard Rd.

Speed limit:	45/55 mph
Pavement:	Asphalt with joints
	Concrete with joints
Distance:	14.9 miles

Section 7 - Packard Rd. to Clinton Trail (US-50)

Speed limit:	45 mph
Pavement:	Asphalt
Distance:	1.4 miles

Section 8 - Clinton Trail (US-50) to US-43

Speed limit:	55 mph

Pavement: Asphalt with cracks

Smooth asphalt

Asphalt with longitudinal cracks

Distance: 17 miles

Section 9 - US-43 to US-66 to I-96

Speed limit: 55 mph

Pavement: Concrete with joints

Distance: 9.7 miles

Section 10 - I-96 to College Rd.

Speed limit: 55 mph

Pavement: Concrete with joints

Distance: 39.1 miles

Each shipment consisted of a combination of one of two trailer lading weights and one of three suspension systems. The ladings used were:

a) 5,000 pounds

b) 18,000 pounds

The suspensions used were:

a) Conventional air-ride suspension (maintained properly) refered to as air up (See Figure 1)

b) Damaged air-ride suspension (air bled out) refered to as air down (See Figure 1)

c) Conventional leaf spring suspension
    refered to as leaf (See Figure 2)

The following combinations were used for the six shipments:

Shipment 1

Trailer: 48 feet x 99 inches (width) x 108 inches (height)

Great Dane - Tandem Axle

Conventional air-ride suspension (maintained properly)

Load: 5000 pounds of miscellaneous computer goods

Instrumentation: (See Figure 3)

2 vertical accelerometers - mounted to trailer bed.

Front - accelerometer located 55.5 inches from front, inside of trailer, 50.5 inches from the left side of trailer.

Rear - accelerometer located 68.0 inches from the inside rear of trailer, 50.0 inches from the left side of trailer.

Shipment 2

Trailer: 48 feet x 99 inches (width) x 108 inches (height)

Great Dane - Tandem Axle

Damaged air-ride suspension (air bled out)

Load: 5000 pounds of miscellaneous computer goods

Instrumentation: (See Figure 3)

2 vertical accelerometers - mounted to trailer bed.

Front - accelerometer located 55.5 inches from front, inside of trailer, 50.5 inches from the left side of trailer.

Rear - accelerometer located 68.0 inches from the inside rear of trailer, 50.0 inches from the left side of trailer.

Shipment 3

Trailer: 48 feet x 99 inches (width) x 108 inches (height)

Great Dane - Tandem Axle

Conventional air-ride suspension (maintained properly)

Load: 18,000 pounds of miscellaneous computer goods

Instrumentation: (See Figure 3)

2 vertical accelerometers - mounted to trailer bed.

Front - accelerometer located 55.5 inches from front, inside of trailer, 50.5 inches from the left side of trailer.

Rear - accelerometer located 68.0 inches from the inside rear of trailer, 50.0 inches from the left side of trailer.

Shipment 4

Trailer: 48 feet x 99 inches (width) x 108 inches (height)

Great Dane - Tandem Axle

Damaged air-ride suspension (air bled out)

Load: 18,000 pounds of miscellaneous computer goods

Instrumentation: (See Figure 3)

2 vertical accelerometers - mounted to trailer bed.

Front - accelerometer located 55.5 inches from front, inside of trailer, 50.5 inches from the left side of trailer.

Rear - accelerometer located 68.0 inches from the inside rear of trailer, 50.0 inches from the left side of trailer.

Shipment 5

Trailer: 48 feet x 99 inches (width) x 110 inches (height)

Lufkin - Tandem Axle

Conventional Leaf Spring

Load: 5,000 pounds of miscellaneous computer goods

Instrumentation (See Figure 3)

Two vertical accelerometers - mounted to trailer bed.

Front - accelerometer located 56.0 inches from the front, inside of trailer, 47.5 inches from the left side of trailer.

Rear - accelerometer located 68.0 inches from the inside rear of the trailer, 52.0 inches from the left side of trailer.

Shipment 6

Trailer: 48 feet x 99 inches (width) x 110 inches (height)

Lufkin - Tandem Axle

Conventional Leaf Spring

Load: 18,000 pounds of miscellaneous computer goods

Instrumentation (See Figure 3)

Two vertical accelerometers - mounted to trailer bed.

Front - accelerometer located 56.0 inches from the front, inside of trailer, 47.5 inches from the left side of trailer.

Rear - accelerometer located 68.0 inches from the inside rear of the trailer, 52.0 inches from the left side of trailer.

To monitor the truck shipments, piezoelectric accelerometers were used, one for front vertical motion and one for rear vertical motion. These accelerometers were mounted to aluminum blocks and these in turn were screwed to the trailer floor. The sensor type and their sensitivity values are outlined in Table 1. Micro-dot cables were used to connect the accelerometers to Kistler (model 5112) signal conditioners. The output from the conditioner was connected to a Teac XR-310 FM cassette recorder (Figure 4). An oscilliscope was used to perform a cross check and to calibrate the system before each shipment. The recorder was used to record the output from the signal conditioners onto magnetic tapes. During each run, voice input was recorded onto the tape to indicate the begining and ending of each section.

Only five sections of the entire shipment were analyzed, section 3, 6, 8, 9, and 10. This was due to the shortness in length of some sections and that some road surfaces were repeated in the shipments. The experimental design for the analyzed data is outlined in Table 2.

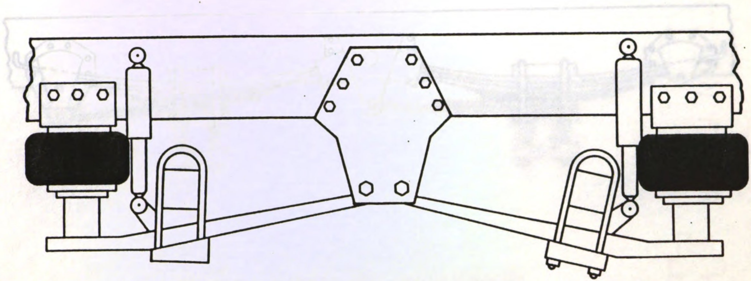

Figure 1. A Typical Air-Ride Suspension

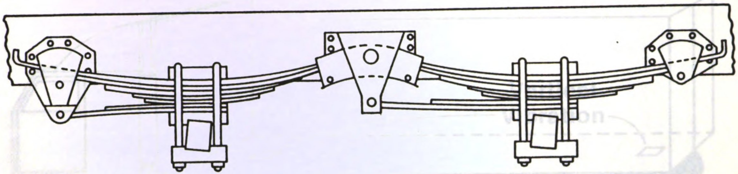

Figure 2. A Typical Leaf Spring Suspension

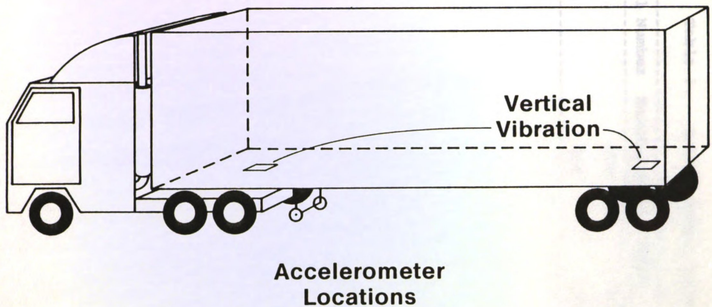

Figure 3. Location of Instrumentation

Table 1. Accelerometer Information

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

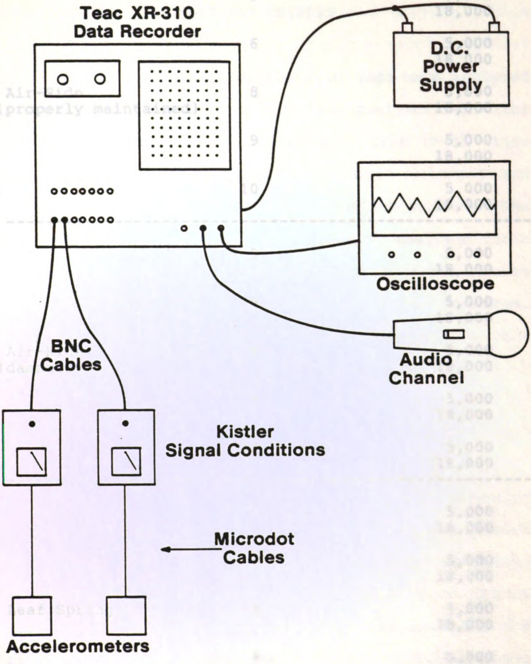

Figure 4. Setup of Data Acquisition System

Table 2. Experimental Design

Suspension	Section	Lading
	3	5,000
		18,000
	6	5,000
		18,000
Air-Ride (properly maintained)	8	5,000
		18,000
	9	5,000
		18,000
	10	5,000
		18,000
	3	5,000
		18,000
	6	5,000
		18,000
Air-Ride (damaged)	8	5,000
		18,000
	9	5,000
		18,000
	10	5,000
		18,000
	3	5,000
		18,000
	6	5,000
		18,000
Leaf Spring	8	5,000
		18,000
	9	5,000
		18,000
	10	5,000
		18,000

4.0 DATA AND RESULTS

The vibration data recorded on magnetic tape was analyzed using a Schumberger 1209 Random Vibration Analyzer/Conroller and Power Density Plots were printed on a Team TP-35 Video Hard Copy Printer. These plots were later enlarged and redrawn to aid in the readability of the desired numbers. The random vibration analyzer performs a spectral analysis for a given section of the tape recorded data, and produced a Power Density Value for each component frequency of the spectrum, as described in Appendix A. The Bandwidth used was 1 Hz. for the analysis.

Trailer Vibration:

Figure 5 shows the background noise levels for the recording and analyzing equipment. The average RMS level for this plot was 0.00192 g. This is about 1.5% of normal RMS values obtained for various trips on different roads. Line current which operates at 60 cycles per second is the cause for the spike at 60 Hz. Figure 6 shows the vertical vibration levels in the trailer caused by the tractor engine running. The levels for this plot showed an average RMS of 0.0398 g. The peak was seen at 50 Hz.

Tables B-1 through B-10, located in Appendix B, show the power density values at specific frequencies for the various road conditions and lading weights used. Figures 7 through 16 show the Power Density Plots that were developed from the same road sections and lading weights. Figures 7 through 16 are located at the end of this section.

Due to the fact that all Power Density levels for the front of the trailer were lower than those in the rear, only the values and plots for the rear of the trailer will be presented.

Generally, a P.D. plot will be characterized by three main sections. In the 1 - 10 Hz. range, a peak will correspond to the natural frequency of the trailer's suspension system. The levels in this range can result in large displacements and therefore are usually responsible for most damage to products in distribution. A peak in the 10 - 50 Hz. range is historically documented as being caused by the resonant frequency of the trailer structure. In this range there can often be more than one peak due to sub-harmonics of different panels used to make the trailer. Above 50 Hz., a P.D. level of 1.24×10^{-1} is needed to produce 0.5 g. This will give a stroke of 0.00195 inches (the stroke will even be smaller at frequencies above 50 Hz.). A Power Density level of this magnitude is very difficult to achieve in the distribution system measured in this study. Even if this level is reached, the stroke is so small that damage is unlikely to most packaged products. These peaks are generated by road irregularities. A brief summary of Figures 7 through 16 will now be given.

Figure 7 shows vertical vibration spectrums for trailers having air-ride suspension (maintained properly), air ride suspension (damaged), and leaf-spring suspension. All these trailers had a load of 5000 lbs. traveling 30 mph on asphalt with severe cracking (section 3). The air-ride (maintained) spectrum shows a the first peak at 2 Hz., with much smaller peaks at 9 Hz. and 23 Hz. The spectrum for the damaged air-ride suspension had a dominant peak at a frequency of 5 Hz. and smaller peaks at frequencies of 17 Hz. and 30 Hz. Leaf-spring suspension gave a spectrum with a major peak at 4-5 Hz. and smaller peaks at 20 Hz. and 30-40 Hz. The peaks at lower frequencies, 2-5 Hz., correspond to the suspension system of the trailer. Peaks between 10 and 40 Hz. correspond to the trailer structure resonances. Table B-1 shows, that the maintained air-ride suspension had significantly lower levels at all frequency levels than that of the damaged air-ride or leaf-spring suspension. The damaged air-ride and leaf-spring suspension had very similar levels at similar frequencies up to 30 Hz. where the leaf-spring suspension then showed slightly higher levels.

Figure 8 shows vertical vibration spectrums for the same suspensions as above with a lading of 5000 lbs., but over asphalt with joints and concrete with joints at vehicle speeds of 45-55 mph (section 6). The spectrum for maintained air-ride suspension showed a suspension response at 2 Hz. and a structural response at a frequency of 19 Hz. The damaged air-ride suspension showed a suspension response at a frequency of 5 Hz. and a structural response at 20 Hz. and 50 Hz. The leaf-spring suspension showed a suspension response at 5 Hz. with structural responses at 20 Hz. and 40 Hz. Table B-2 shows that the maintained air-ride had levels at low frequency which were on the order of 10 times lower than that of the damaged air-ride. The leaf-spring had a Power Density value which was significantly lower than that of damaged air-ride at low frequencies. The levels after 10 Hz. became very similar.

Figure 9 shows vertical vibration spectrums for trailers having a lading of 5000 pounds and the following suspensions: air-ride (maintained properly), air ride (damaged), and leaf-spring. All these trailers traveled 55 mph on asphalt with cracks, smooth asphalt, and asphalt with longitudinal cracks (section 8). The air-ride (maintained) spectrum shows a suspension response at 2 Hz., with structural responses at 7 Hz. and 20 Hz. and 30 Hz. The spectrum for the damaged air-ride suspension had a suspension resonance at a frequency of 5 Hz. and structural responses at frequencies of 18 Hz., 33

Hz., 50 Hz. Leaf-spring suspension gave a spectrum with a response due to suspension at 5 Hz. and structural responses at 17 Hz., 40 Hz. Table B-3 shows that the maintained air-ride suspension had significantly lower levels at all frequency levels. The damaged air-ride suspension had higher levels at low frequencies than that of the leaf-spring. After 6 Hz. the levels became similar.

Figure 10 shows vertical vibration spectrums for the three suspensions as above with a lading of 5000 lbs. and traveling over rural roads made of concrete with joints at a speed of 55 mph (section 9). Maintained air-ride suspension showed a suspension response at 2 Hz. and structure response at a frequency of 20 Hz. The damaged air-ride suspension showed a suspension response at a frequency of 4-5 Hz. with structure responses at 19 Hz. and 50 Hz. The leaf-spring suspension showed a response to suspension at 5 Hz. with structure responses at 19 Hz. and 40 Hz. Table B-4 shows that the maintained air-ride had vibration levels at most frequency which were on the order of 10 times lower than that of the damaged air-ride. The leaf-spring gave levels which were lower than that of damaged air-ride at low frequencies. At high frequencies the leaf spring had the highest levels.

Figure 11 shows vertical vibration spectrums for trailers having air-ride suspension (maintained properly), air ride suspension (damaged), and leaf-spring suspension. All these trailers had a load of 5000 lbs. traveling 55 mph on concrete with joints (section 10). The air-ride (maintained) spectrum shows no significant response to the trailer suspension although its highest power density value was at 2 Hz. The spectrum for the damaged air-ride suspension showed a response to the suspension at 5 Hz. and a structural response at frequencies of 17 and 37 Hz. The Power Density Spectrum for leaf-spring suspension has a suspension response at 5 Hz. and structural responses at 20 Hz., 30 Hz., and 50 Hz. Table B-5 shows that the maintained air-ride suspension had vibration levels at all frequencies that were up to 1000 times less than the other suspension systems. The damaged air-ride had a level which was 3 times that of the leaf-spring suspension at low frequencies. At mid to high frequencies the levels for leaf-spring and damaged air-ride were very similar.

Figure 12 shows vertical vibration spectrums for the same suspensions as above, with a lading of 18,000 lbs. traveling over asphalt with severe cracks at a speeds of about 30 mph (section 3). The maintained air-ride suspension showed a suspension response at 2 Hz., and structural responses at 10 Hz., 27 Hz. and 33 Hz. The damaged air-ride suspension showed a peak corresponding to suspension at a frequency of 4 Hz. with structural responses at 10 Hz., 17 Hz. and 21 Hz. The leaf-spring suspension showed a peak at 4 Hz. with structural responses at frequencies of 10 Hz., 21 Hz., 40 Hz., and 60 Hz.

Table B-6 shows that the maintained air-ride suspension had the lowest power density levels throughout the spectrum. The damaged air-ride had a higher level at low frequencies, after which leaf-spring suspension had the highest power density levels.

Figure 13 shows vertical vibration spectrums for trailers having the three different suspension systems. All these trailers had a load of 18,000 lbs. traveling 45 - 55 mph on asphalt with joints and concrete with joints (section 6). The air-ride (maintained) spectrum shows a suspension response at 2 Hz., with structural responses at 20 Hz., 30 Hz., and 50 Hz. The spectrum for the damaged air-ride suspension had a response to suspension at 4 Hz. and structural responses at frequencies of 21 Hz., and 40 Hz. Leaf-spring suspension showed a suspension response with a gradually rising peak from 3 to 5 Hz. and structural responses at 11 Hz. and 40 Hz. Table B-7 shows that all suspensions had similar levels at low frequencies. At frequencies beyond 10 Hz. the leaf-spring suspension showed the highest power density.

Figure 14 shows vertical vibration spectrums for the same trailer suspensions with a lading of 18000 lbs., over asphalt with cracks, smooth asphalt and asphalt with longitudinal cracks at a speed of 55 mph (section 8). The P.D. plot for maintained air-ride suspension shows a suspension response at 2 Hz. The damaged air-ride suspension showed a response to suspension at a frequency of 4 Hz. and structural responses at 21 Hz. and 30 Hz. The leaf-spring suspension shows a flat peak from 3 to 5 Hz. due to the suspension with structural responses at 11 Hz., 21 Hz., and 40 Hz. Table B-8 shows the maintained air-ride had levels which were lower than that of the damaged air-ride and leaf-spring, however, the difference wasn't that large. The leaf-spring gave levels slightly higher than that of damaged air-ride at low frequencies and damaged air-ride had a higher level at high frequencies.

Figure 15 shows vertical vibration spectrums for trailers having air-ride suspension (maintained properly), air ride suspension (damaged), and leaf-spring suspension. All these trailers had a load of 5000 lbs. traveling 30 mph on asphalt with severe cracking (section 9). The air-ride (maintained) spectrum shows a suspension response at 2 Hz., with much smaller structural response at 9 Hz. and 23 Hz. The spectrum for the damaged air-ride suspension had a response to suspension at 5 Hz. and structural responses at frequencies of 17 Hz. and 30 Hz. Leaf-spring suspension showed a suspension response at 4-5 Hz. and structural responses at 20 Hz. and 30-40 Hz. Table B-9 shows that the maintained air-ride suspension had significantly lower levels then the other two suspensions at all frequency levels. The damaged air-ride and leaf-spring suspension had very similar levels.

Figure 16 shows vertical vibration spectrums for the same suspensions as above with a lading of 5000 lbs., but over asphalt with few cracks at a speed of 30 mph (section 10). The spectrum for maintained air-ride suspension showed suspension response at 2 Hz. and a structural response at 19 Hz. The damaged air-ride suspension showed a much more severe suspension response at a frequency of 5 Hz. with a structural response at 20 Hz. The leaf-spring suspension showed a peak at 5 Hz. corresponding to the suspension. Structural response was shown at 20 Hz. and 40 Hz. Table B-10 shows the maintained air-ride had levels at low frequency which were on the order of 10 times lower than that of the damaged air-ride. The leaf-spring gave levels slightly higher than that of maintained air-ride up to frequencies of 40 Hz., where the leaf-spring suspension became the worst of the three. Tables 3 and 4 summarize the Power Density values of all data spectrums discussed in the above paragraphs.

In general, for a lightly loaded truck a maintained air-ride trailer shows two pronounced peaks, at 2 Hz. and 20 - 30 Hz. The damaged air-ride trailer shows two pronounced peaks, at 5 Hz. and at 20 Hz. Leaf-spring suspension trailers show two pronounced peaks, at 5 Hz. and at 30 - 40 Hz.

The vertical vibration levels for the three suspension systems when loaded with a lading of 18,000 pounds, the air-ride (maintained) trailer shows the prominent peak at 2 Hz. The damaged air-ride trailer shows three pronounced peaks, at 4

Hz., 20 Hz, and 50 Hz. Leaf-spring suspension trailer shows peaks which are prominant at 4 Hz., 10 Hz., 21 - 22 Hz., 40 Hz. and 50 Hz.

The power density spectrums for the damaged air-ride and leaf-spring trailers follow very similar contours. The explanation for this is that after the air is bled out of the diaphram in a damaged air-ride suspension, the only remaining suspension is shock absorbers. The damaged air-ride often achieves higher power density levels than that of a leaf-spring suspension due to the fact that the suspension will "bottom out" on rougher road inputs. A maintained air-ride suspension will provide lower power density levels, up to 1000 times lower, at all frequencies with a light load.

Overall vibration levels are the lowest in air-ride trailers. However, lightly loaded trailers show more pronounced differences between the three suspension types. A damaged air-ride shows a shift in suspension frequency from the conventional air-ride suspension. This shift is from 2 to 5 Hz. due to the stiffening of the suspension. Also the damaged air-ride has a higher level in the 4-5 Hz. region as compared to the conventional leaf-spring. Even though the structural response of a leaf-spring is the highest at 50 Hz. as compared to 40 Hz. for the damaged air-ride, the displacements in this frequency range are however not usually great enough to cause product damage.

The effect in lading weight is shown in Figures 17, 18, and 19. A shift in suspension response is shown for both leaf spring and the damaged air-ride system, from 5 Hz. to 4 Hz. The conventional air-ride system showed no effect in suspension response. Typically the power density levels are 3 to 5 times lower with the heavier lading.

Figures 20 through 25 demonstarate the ratio of gRMS versus frequency for conventional leaf spring to conventional air-ride suspensions and conventional leaf spring suspensions to damaged air ride suspensions. These plots represent three different road conditions; Section 3 - intercity roads, Section 6 - two lane county roads, and Section 10 - interstate expressway. For instance at an acceleration ratio of one, the conventional air-ride or damaged air-ride has the same acceleration level as that of leaf spring. At an acceleration ratio of 5 the conventional leaf spring has an acceleration 5 times greater than that of the damaged air-ride or conventional air-ride depending on the respective curve which one is looking at.

These curves show a better performance by the conventional air-ride suspension and similar acceleration levels for damaged air-ride and leaf spring.

Table 3 - Summary of Responses for 5000 lb. Lading

Suspension

Section	Frequency (Hz.) Air	Frequency (Hz.) Damaged	Frequency (Hz.) Leaf	P.D. Level Air	P.D. Level Damaged	P.D. Level Leaf
3	2	5	5	1500	4000	3300
6	2	5	5	9000	70000	20000
8	2	5	5	2000	30000	11000
9	2	5	5	5000	41000	11000
10	2	5	5	1100	50000	20000

Structure

Section	Frequency (Hz.) Air	Frequency (Hz.) Damaged	Frequency (Hz.) Leaf	P.D. Level Air	P.D. Level Damaged	P.D. Level Leaf
3	23	17	20	700	1000	1500
6	20	20	40	1000	3000	6000
8	20	17	17	300	2500	2700
9	20	20	20	330	15000	1500
10	21	20	20	200	2000	2000

All Power Density Levels are x 10^{-6}

Table 4 - Summary of Responses for 18,000 lb. Lading

	Suspension					
	Frequency (Hz.)			P.D. Level		
Section	Air	Damaged	Leaf	Air	Damaged	Leaf
3	2	4	4	800	3000	1300
6	2	4	5	5300	15000	5000
8	2	4	5	1100	5000	1300
9	2	4	5	5300	13000	3700
10	2	4	5	4000	10000	2000

	Structure					
	Frequency (Hz.)			P.D. Level		
Section	Air	Damaged	Leaf	Air	Damaged	Leaf
3	10	10	10	530	900	6000
6	20	20	40	900	1300	2000
8	30	21	21	500	1500	1500
9	21	21	21	250	2000	2000
10	20	21	21	210	1100	1100

All Power Density Levels are x 10^{-6}

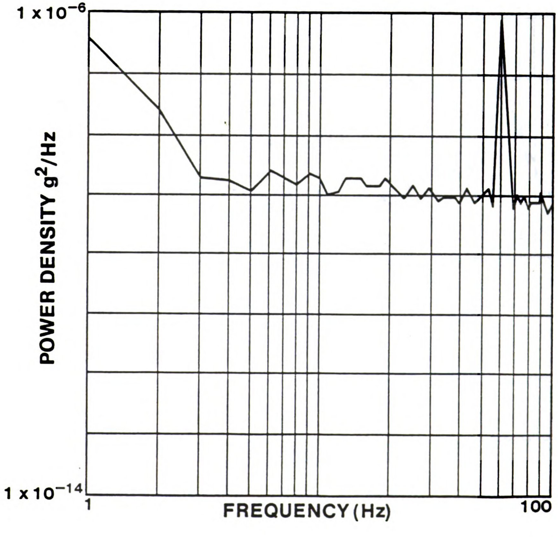

Figure 5. Vertical Rear Trailer Vibration: Background Noise for Analyzing Equipment

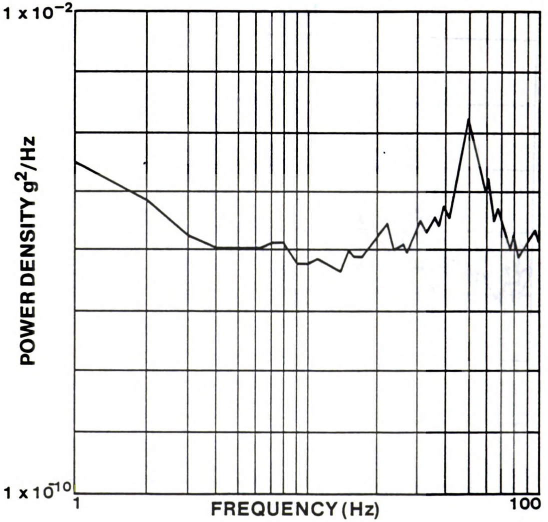

Figure 6. Vertical Rear Trailer Vibration: Engine Noise for Stationary Truck

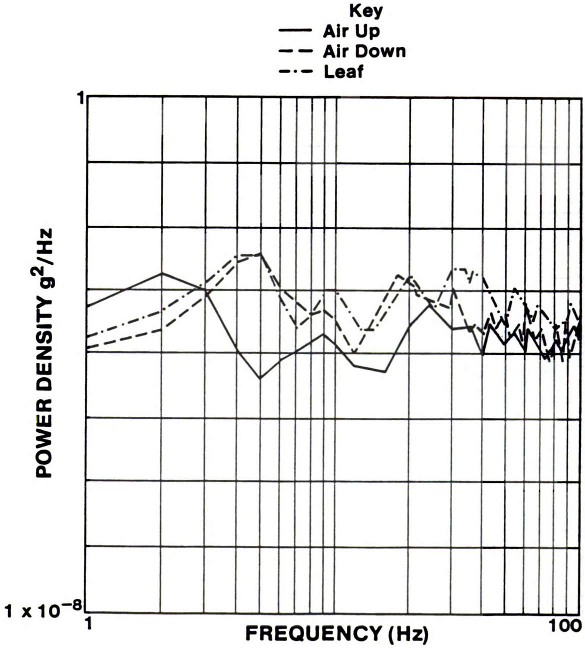

Figure 7. Vertical Rear Trailer Vibration for Asphalt With Severe Cracks, 30 mph (Section 3); Load: 5000 lbs.

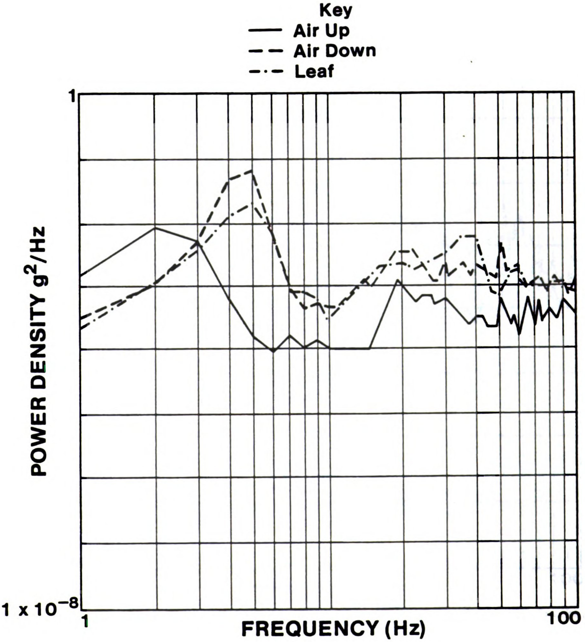

Figure 8. Vertical Rear Trailer Vibration for Asphalt With Joints, Concrete With Joints, 45-55 mph (Section 6); Load: 5000 lbs.

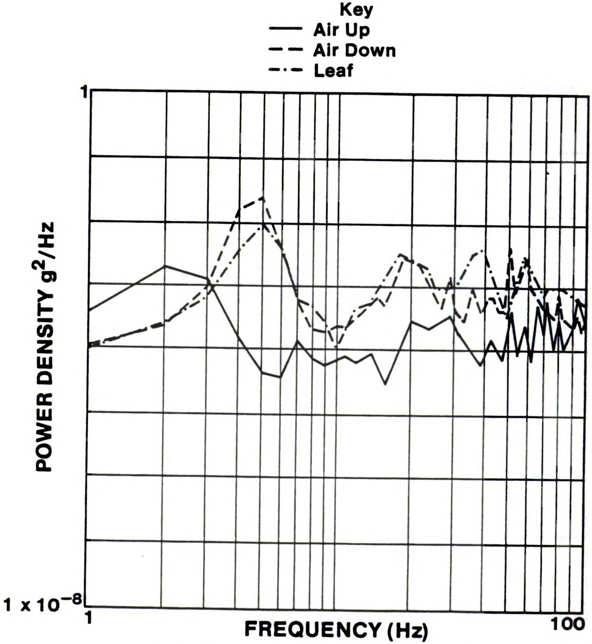

Figure 9. Vertical Rear Trailer Vibration for Asphalt With Cracks, Smooth Asphalt, 55 mph (Section 8); Load 5000 lbs.

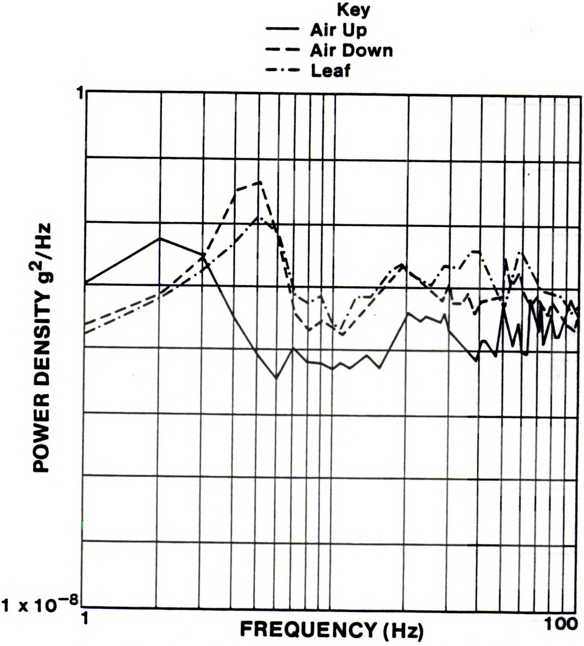

Figure 10. Vertical Rear Trailer Vibration for Concrete With Joints, 55 mph (Section 9); Load: 5000 lbs.

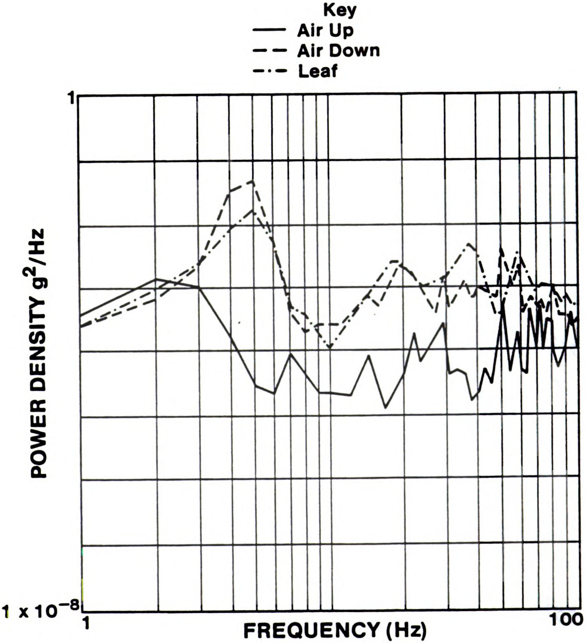

Figure 11. Vertical Rear Trailer Vibration for Concrete With Joints, 55 mph (Section 10); Load: 5000 lbs.

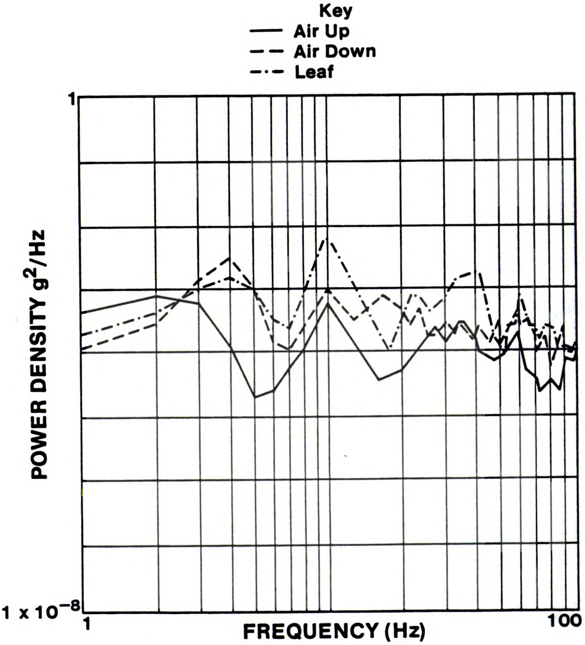

Figure 12. Vertical Rear Trailer Vibration for Asphalt With Severe Cracks, 30 mph (Section 3); Load: 18,000 lbs.

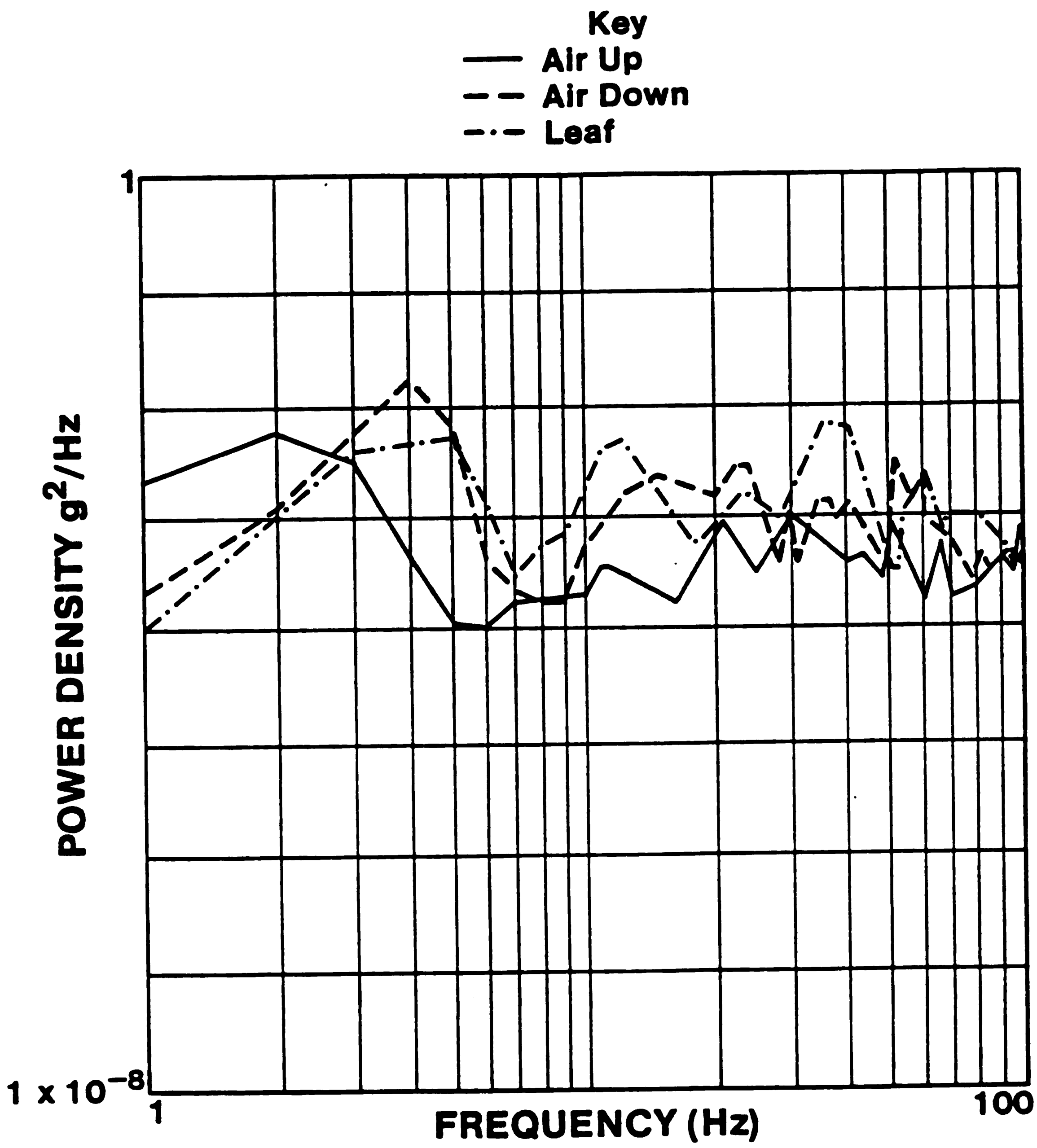

Figure 13. Vertical Rear Trailer Vibration for Asphalt With Joints, Concrete With Joints, 45-55 mph (Section 6); Load: 18,000 lbs.

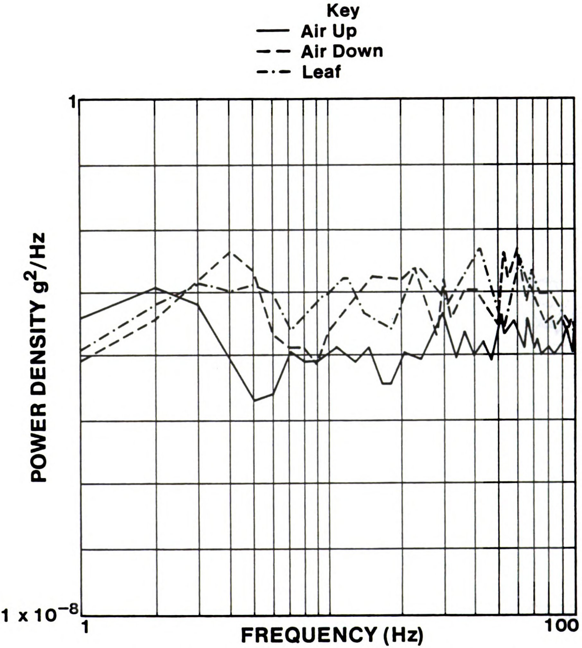

Figure 14. Vertical Rear Trailer Vibration for Asphalt With Cracks, Smooth Asphalt, 55 mph (Section 8); Load: 18,000 lbs.

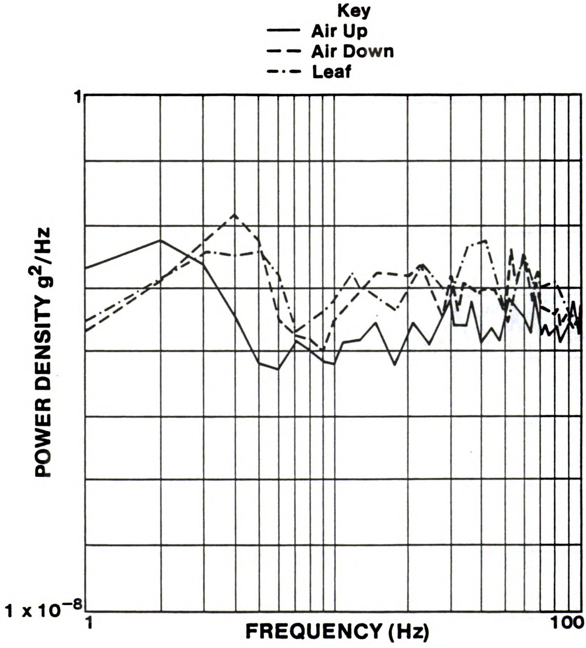

Figure 15. Vertical Rear Trailer Vibration for Concrete With Joints, 55 mph (Section 9); Load: 18,000 lbs.

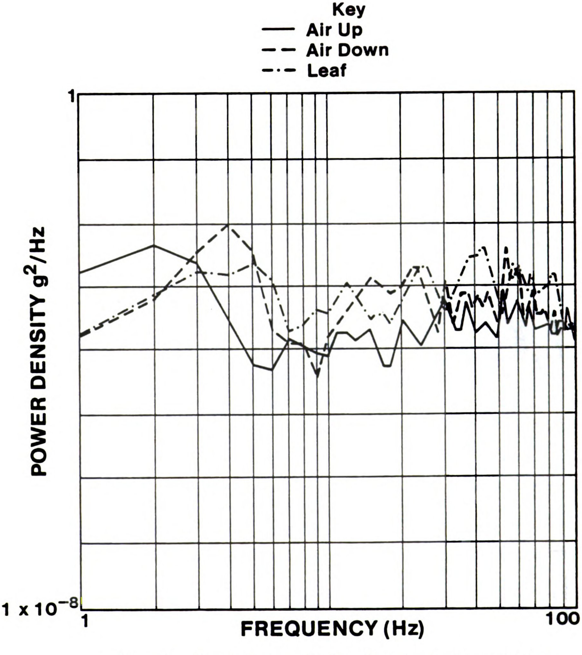

Figure 16. Vertical Rear Trailer Vibration for Concrete With Joints, 55 mph (Section 10); Load: 18,000 lbs.

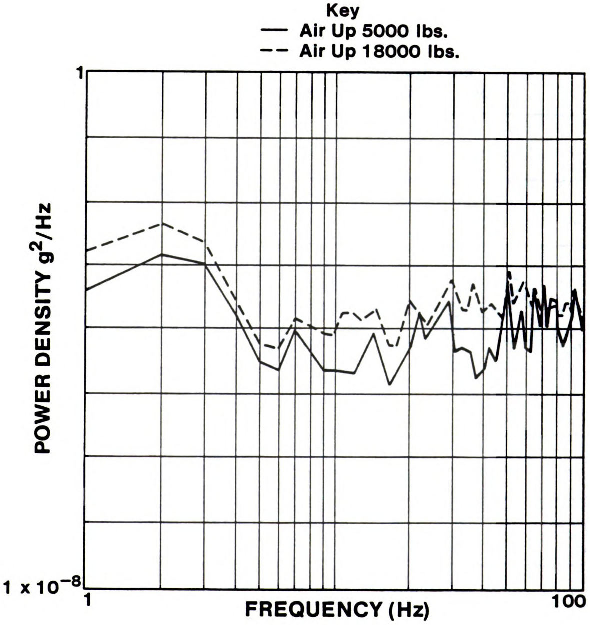

Figure 17. Vertical Rear Trailer Vibration for Concrete With Joints, 55 mph (Section 10); Conventional Air Ride Suspension.

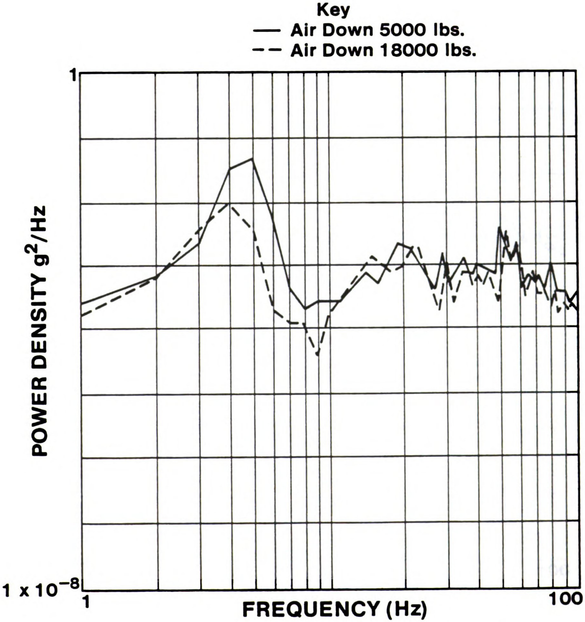

Figure 18. Vertical Rear Trailer Vibration for Concrete With Joints, 55 mph (Section 10); Damaged Air Ride Suspension

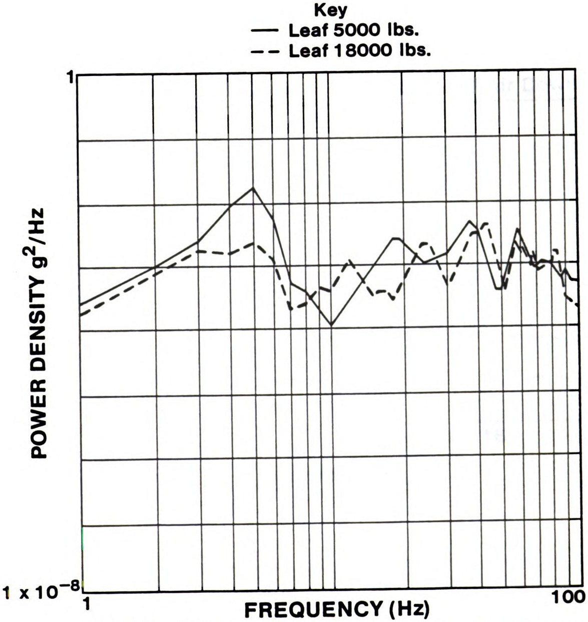

Figure 19. Vertical Rear Trailer Vibration for Concrete With Joints 55 mph (Section 10); Conventional Leaf-Spring Suspension.

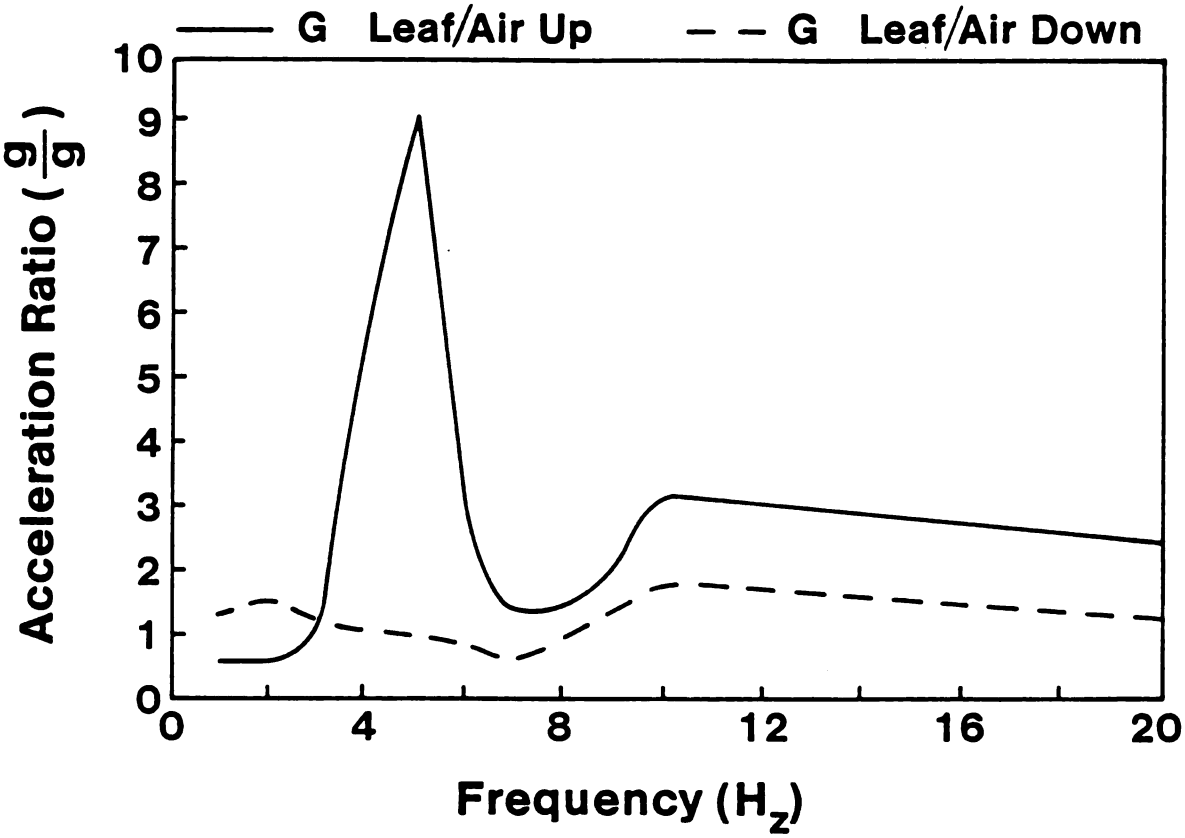

Figure 20. Accelration Ratio versus Frequency for Road Section 3, 5000lb. Load.

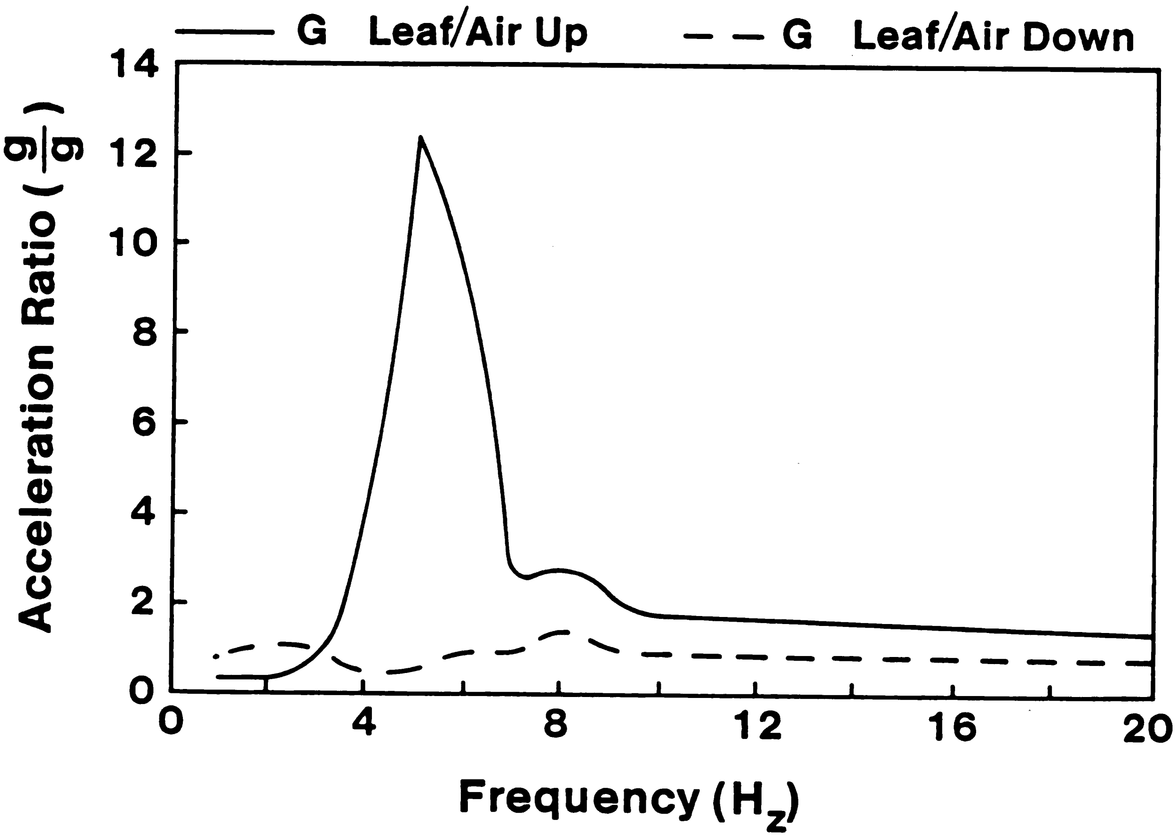

Figure 21. Acceleration Ratio versus Frequency for Road Section 6, 5000lb. Load.

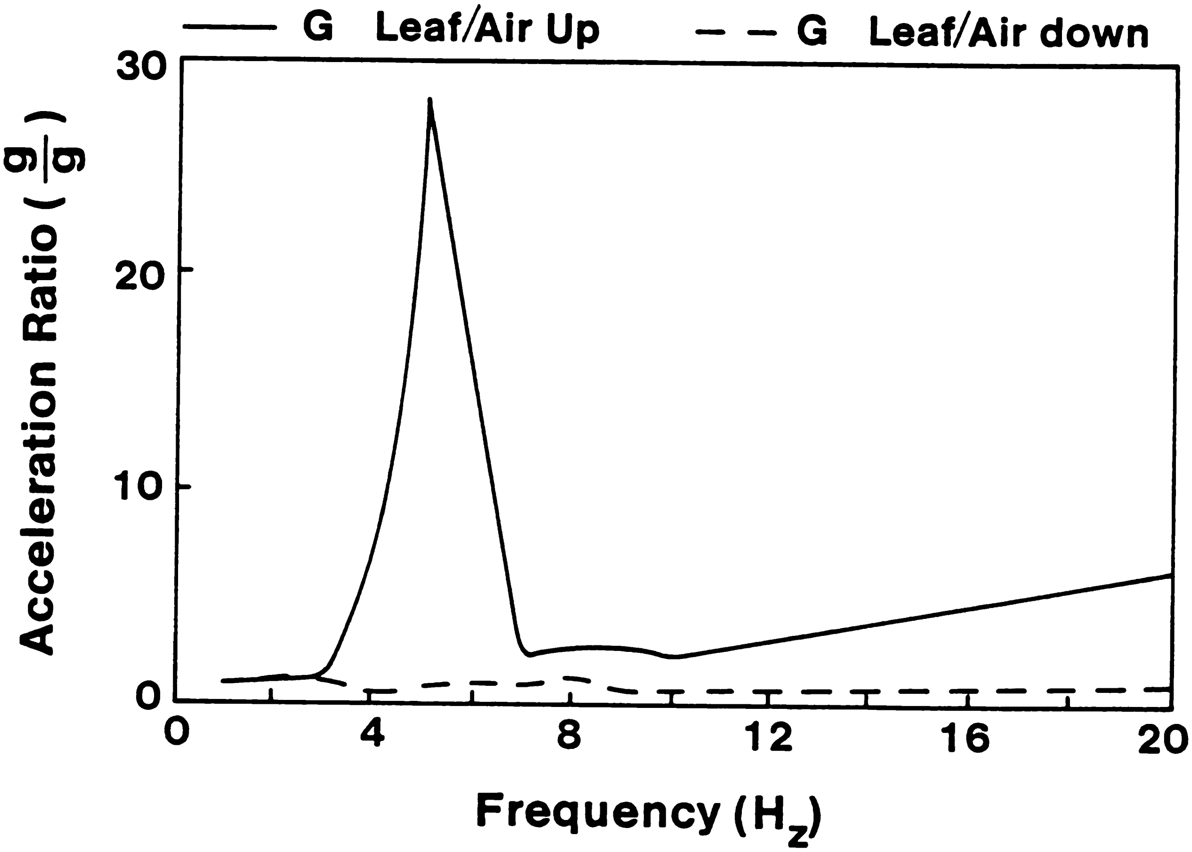

Figure 22. Acceleration Ratio versus Frequency for Road Section 10, 5000lb. Load.

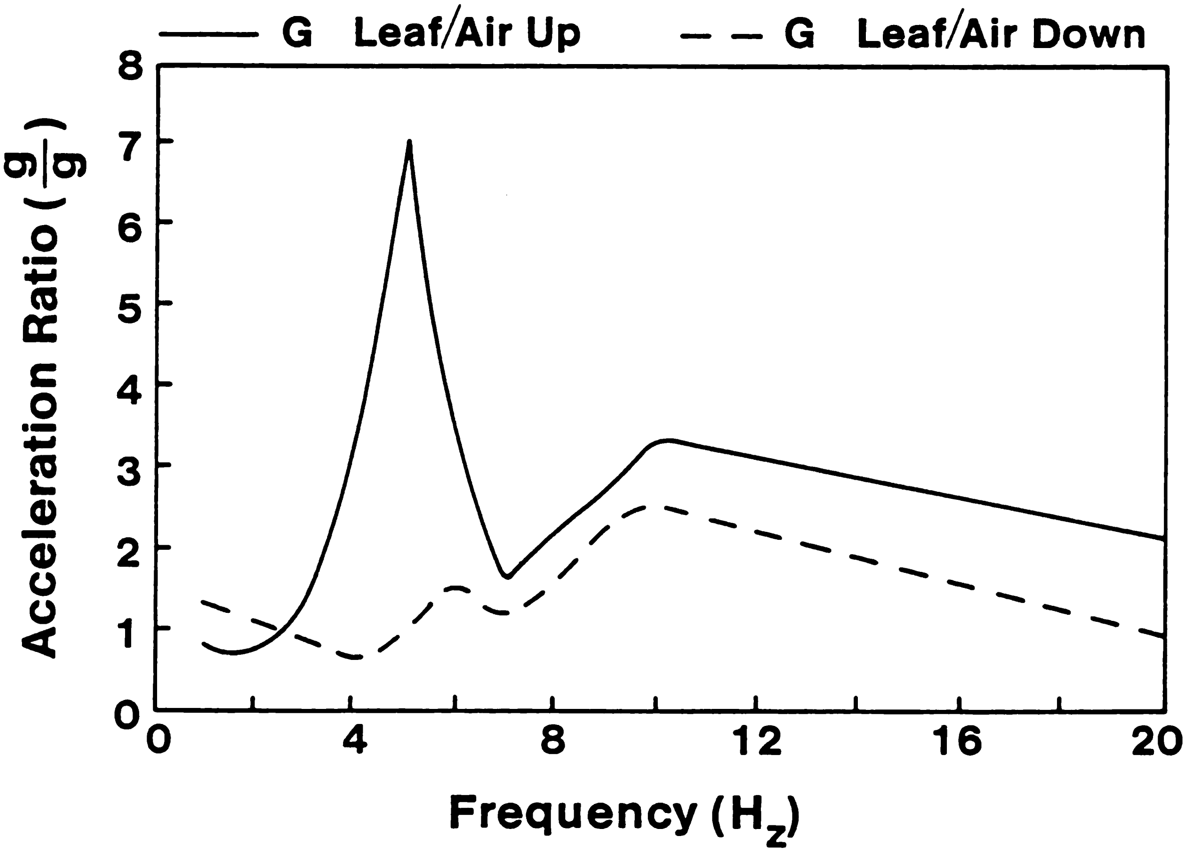

Figure 23. Acceleration Ratio versus Frequency for Road Section 3, 18,000lb. Load.

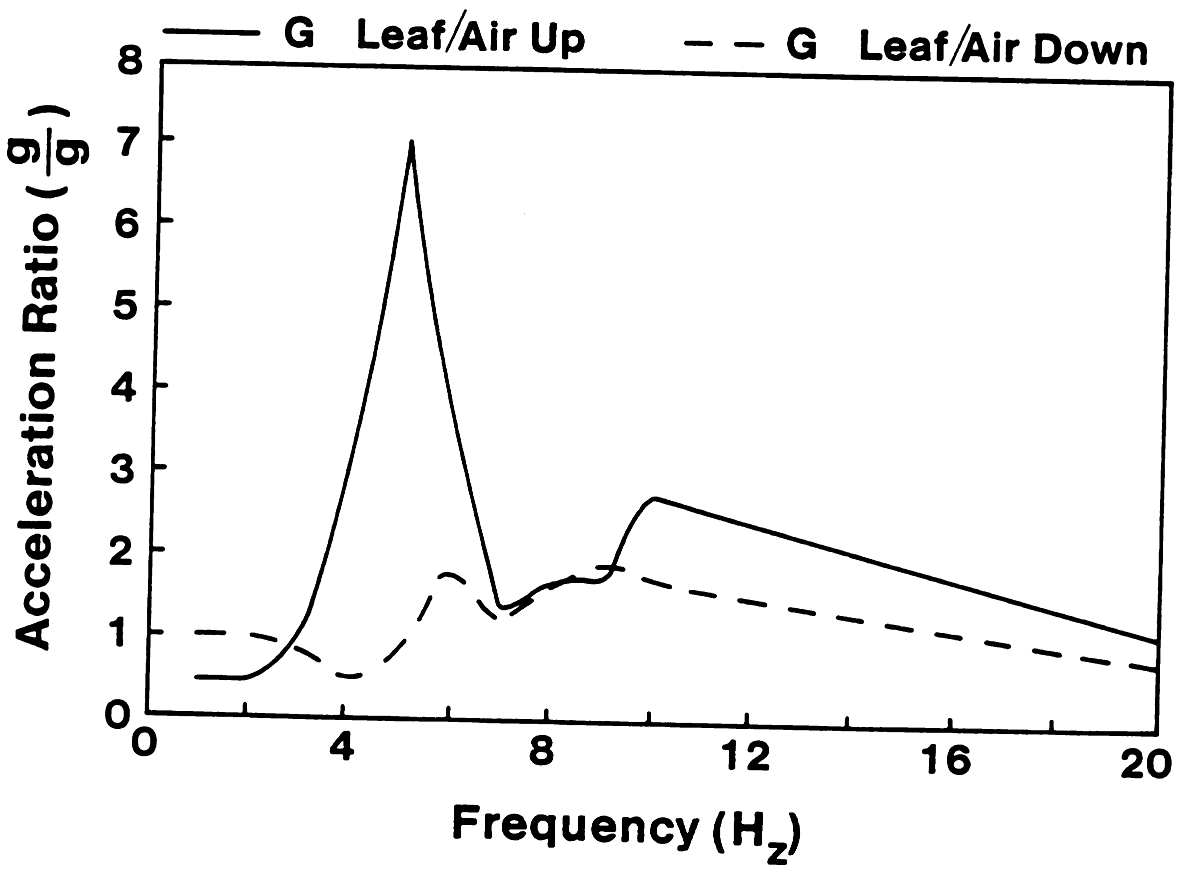

Figure 24. Acceleration Ratio versus Frequency for Road Section 6, 18,000lb. Load.

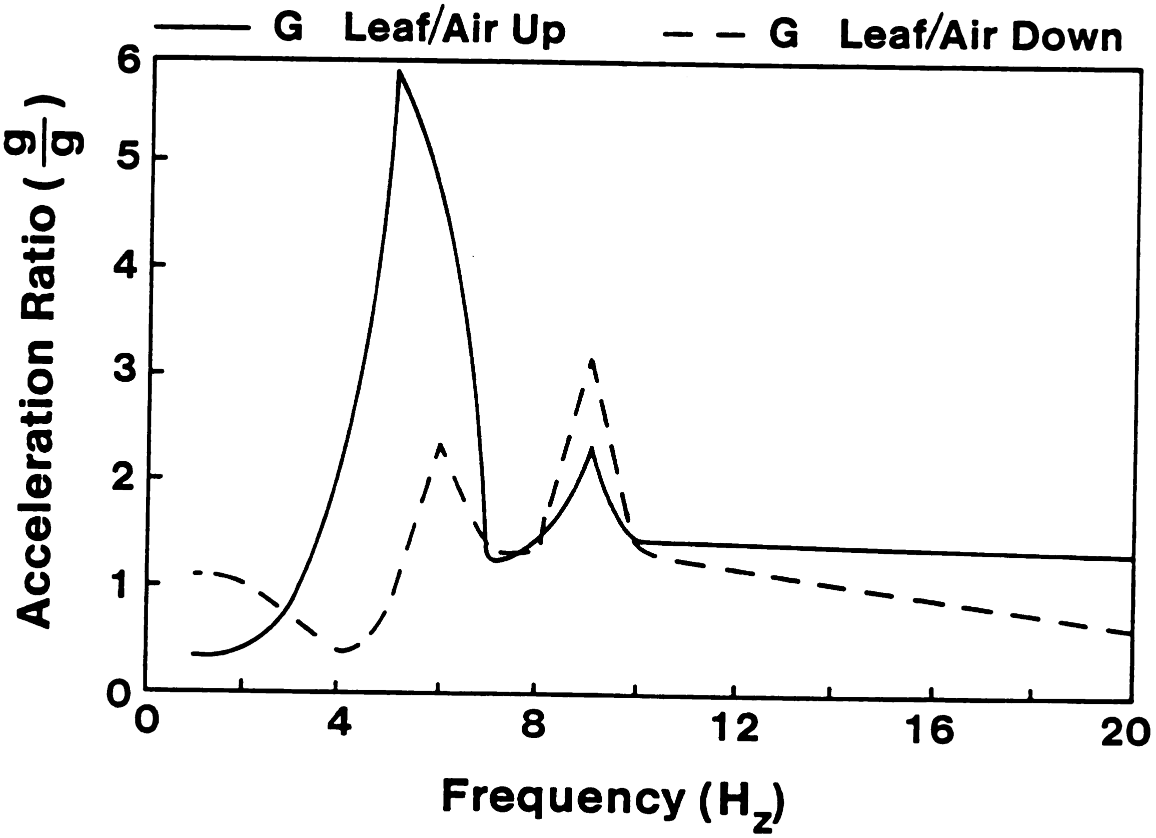

Figure 25. Acceleration Ratio versus Frequency for Road Section 10, 18,000lb. Load.

5.0 Conclusions And Recomendations

The following conclusions were made by this study:

1) Conventional air-ride suspension shows a suspension response at 2 Hz. Damaged air-ride shows a suspension response at 5 Hz. with a light load and 4 Hz. for a heavy load. The effect of increased weight is seen in the suspension response for the leaf-spring and damaged air-ride suspension systems. The response decreased from 5 Hz. to 4 Hz.

2) Power Density levels at frequencies between 1 and 5 Hz. are the highest with Damaged air-ride suspension and the lowest with the conventional air-ride system. The levels are up to 1000 times higher in the damaged air-ride.

3) Structural responses for all three suspension systems are in the range of 17 Hz. to 23 Hz. Also at frequencies above 50 Hz. displacements measured are very small and will have little effect in damage to packaged product.

4) Based on the comparison between the two suspensions, the air cushion produces higher vibration levels between 1 and 3 Hz. as compared to leaf spring. Beyond 3 Hz., the leaf spring generally shows higher vibration levels.

5) Road irregularities due to cracks, railroad tracks, groved pavement, etc., contribute to the vibration levels but show little difference in the performance of suspension types for higher frequencies.

The study also recommends to analyze peak acceleration and related duration for all transient levels to compare air-ride suspensions to leaf spring suspensions.

APPENDICES

APPENDIX A

VIBRATION CONCEPTS

There are two methods to simulate varying vibration levels:

1) Frequency Domain
2) Time Domain

The theory of Time Domain is to exactly reproduce a segment of the distribution system. This method has many drawbacks which limit its application in the area of distribution simulation (Singh, Young, 1988). Frequency Domain uses random vibration to simulate the environment, and is making a significant contribution in this area (Tustin, 1984). The frequency domain method is presented in the from of PD plots, or Power Density plots. Power Density values are calculated by the formula:

$$PD = \frac{\sum_{i=1}^{N} (RMS)_i^2 / N}{BW}$$

where (RMS)i is the Root Mean Square acceleration value measured in g's at any given for a given frequency. N is the number of instants sampled at that frequency. BW is the bandwidth of the band pass filter.

The corresponding PD is then plotted for the given frequency. This plot describing the Power Density versus frequency is called the Power Density Spectrum.

In terms of statistics, the power density at any given frequency is the varience about a mean value equal to zero acceleration. Based on the probabilities associated with the normal Gaussian distribution, we may predict the level of acceleration that is associated with any of the component frequencies of the complex waveform.

Accelerations are characterized in the following manner:

Accelerations of +/- 1 PD values occur 68.3% of the time.

Accelerations of +/- 2 PD values occur 95.4% of the time.

Accelerations of +/- 3 PD values occur 99.7% of the time.

Appendix B

Table B-1 Section 3 5000 lb.
30 mph on Asphalt w/ Cracks

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$) AIR UP	AIR DOWN	LEAF
1	500	110	170
2	1500	200	470
3	1000	900	1300
4	100	3000	3300
5	40	4000	3300
6	80	1000	730
7	100	600	200
8	150	400	400
9	200	430	900
10	100	300	1000
20	250	1000	1500
30	250	1000	2000
40	130	200	1300
50	130	400	300
60	110	600	600
70	100	200	500
80	130	300	300
90	200	100	400
100	130	300	300

Table B-2 Section 6 5000 lb.
45-55 mph on Asphalt/Concrete w/ Joints

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$)		
	AIR UP	AIR DOWN	LEAF
1	1500	300	200
2	9000	1000	1100
3	5000	4300	4000
4	600	50000	11000
5	130	70000	20000
6	90	9000	8000
7	150	1000	1000
8	100	430	800
9	130	500	600
10	100	330	300
20	1000	3000	2000
30	530	1300	3000
40	300	2000	6000
50	500	5000	700
60	130	1100	1100
70	300	1100	1100
80	300	1000	1000
90	400	900	1000
100	300	1000	800

Table B-3 Section 8 5000 lb.
55 mph on Asphalt w/ Cracks

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$)		
	AIR UP	AIR DOWN	LEAF
1	300	110	100
2	2000	210	250
3	1000	1000	700
4	100	13000	4000
5	40	30000	10000
6	35	4000	3300
7	100	600	900
8	73	200	400
9	60	200	230
10	70	210	100
20	300	2500	2700
30	200	1300	1000
40	100	400	2300
50	400	4000	400
60	100	2000	2300
70	200	400	900
80	200	700	1000
90	200	200	600
100	200	310	400

Table B-4 SECTION 9 5000 LBS
55 mph on Concrete w/ Joints

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$) AIR UP	AIR DOWN	LEAF
1	1000	210	150
2	5000	700	550
3	3000	3000	1700
4	270	31000	5000
5	90	41000	11000
6	43	4500	4300
7	100	430	1000
8	70	200	500
9	60	270	700
10	50	200	250
20	330	1500	1500
30	250	1100	2100
40	100	430	3000
50	500	1000	400
60	110	1000	3000
70	200	600	1000
80	310	600	1000
90	230	300	800
100	230	400	450

Table B-5 SECTION 10 5000 LBS
55 mph on Concrete w/ Joints

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$)		
	AIR UP	AIR DOWN	LEAF
1	300	230	270
2	1100	700	1000
3	1000	2300	2500
4	170	31000	10000
5	25	50000	20000
6	20	5000	4300
7	100	400	500
8	43	200	310
9	21	250	170
10	21	250	110
20	50	2000	2000
30	100	1000	1300
40	11	1000	3000
50	100	4000	400
60	100	1000	2000
70	100	400	1000
80	100	1000	1000
90	110	300	700
100	110	250	470

Table B-6 SECTION 3 18,000 LBS
30 mph on Asphalt w/ Cracks

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$)		
	AIR UP	AIR DOWN	LEAF
1	330	110	200
2	800	300	400
3	500	1300	1000
4	110	3000	1300
5	20	1000	1000
6	27	130	300
7	50	100	130
8	100	200	530
9	300	430	2300
10	530	900	6000
20	53	300	250
30	130	250	700
40	100	170	1300
50	80	300	100
60	100	300	700
70	100	100	200
80	40	50	200
90	80	130	130
100	100	100	100

Table B-7 SECTION 6 18,000 LBS
45/55 mph on Asphalt/Concrete w/ Joints

FREQ (HZ)	POWER DENSITY VALUE (x10^{-6})		
	AIR UP	AIR DOWN	LEAF
1	1000	200	210
2	5300	1300	1300
3	3000	5300	3300
4	430	15000	4500
5	100	6300	5000
6	100	400	1300
7	150	200	300
8	150	170	450
9	200	170	630
10	200	500	1500
20	730	1500	1000
30	1000	1000	1300
40	350	1000	5300
50	1000	1000	330
60	200	1000	2300
70	170	500	1000
80	230	330	1000
90	400	350	430
100	700	300	300

Table B-8 SECTION 8 18,000 LBS
55 mph on Asphalt w/ Cracks

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$)		
	AIR UP	AIR DOWN	LEAF
1	400	100	130
2	1100	400	700
3	600	1500	1500
4	100	5000	1000
5	20	2300	1300
6	25	200	1000
7	100	130	270
8	80	130	400
9	80	80	700
10	110	230	1000
20	100	1300	700
30	500	1300	630
40	100	1000	3500
50	300	300	400
60	200	5000	3500
70	130	800	1300
80	110	330	1000
90	150	330	430
100	110	300	230

Table B-9 SECTION 9 18,000 LBS
55 mph on Concrete w/ Joints

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$) AIR UP	AIR DOWN	LEAF
1	2000	210	310
2	5300	1300	1300
3	2300	6000	3700
4	330	13000	3300
5	70	5300	3700
6	53	400	1700
7	130	200	200
8	100	150	300
9	73	100	400
10	70	300	700
20	200	1500	1000
30	600	1500	800
40	130	1000	6000
50	300	1000	300
60	300	3300	3000
70	200	1000	1700
80	270	310	1300
90	210	330	300
100	500	200	300

Table B-10 SECTION 10 18,000 LBS
55 mph on Concrete w/ Joints

FREQ (HZ)	POWER DENSITY VALUE ($x10^{-6}$)		
	AIR UP	AIR DOWN	LEAF
1	1700	170	200
2	4000	600	700
3	2100	3300	1700
4	300	10000	1500
5	60	3000	2100
6	50	200	1100
7	130	110	200
8	100	110	210
9	70	40	400
10	100	110	330
20	210	1000	400
30	600	1100	400
40	170	600	3000
50	230	1000	370
60	500	1000	1500
70	200	500	1000
80	210	200	1000
90	200	210	270
100	110	170	200

LIST OF REFERENCES

American President Companies, Double-Stack/Truck/Vessel Ride Characteristics Study, Equipment Engineering, Dec. 1986.

Antle, J., Measurement of Lateral and Longitudinal Vibration in Commercial Truck Shipments, School of Packaging, Michigan State University, 1989

Caruso H., and Silver, W., Advances in Shipping Damage Prevention, Shock and Vibration Bulletin 46, Part 4, 41-47, 1976

Foley J.T., Preliminary Analysis of Data Obtained in the Joint Army/AEC/Sandia Test of Truck TransportEnvironment, Shock and Vibration Bulletin 35, Part 5, 1966.

Foley J. T., The Environment Experienced by Cargo on a Flatbed Tracor-Trailer Combination, Sandia Laboratories, SC-RR-66-667, 1966.

Goff, J.W.; Grebe, J.; Twede, D. and Townsend, T., You'll Never See It From The Road, Technical Report #26, School of Packaging, Michigan State University, 1984.

Goff, J.W.; Twede, D. and Waldek, J., Research Notes on Examination of The Response of Lading to Transient Excitation By Three Truck Suspension Systems, School of Packaging, Michigan State University, 1988.

Goodwin, D.L., and Holland, R.R., Shock and Vibration Dynamics of Intermodel Distribution Environment - Trailer on a Flat Car, Container in a Well Car, 1987.

Harris, C.M., and C.E. Crede, Shock and Vibration Handbook, Vol. 3, Mc Graw Hill Book Company, N.Y., 1961.

Kelly, R., Comparative Measurement and Analysis of Transportation Vibration Utilizing Leaf Spring and Air Ride Suspension Systems, Presented at The Winter Meeting, American Society of Mechanical Engineers, 1989

Magnuson, C.F., Shock and Vibration Environments for Large Shipping Container During Truck Transport, (Part 1), Sandia Laboratories, SAND 77-1110, 1977.

Magnuson, C.F., Shock and Vibration Environments of Large Shipping Container During Truck Transport, (Part 2),

Marcondes, J. Dynamic Analysis of A Less Than Truckload Shipment, School of Packaging, Michigan State University, 1988.

National Council of Physical Distribution Management, Transportation Strategies For The Eighties, 1982.

Schlue, J.W., The Dynamic Environment of Spacecraft Surface Transportation, Shock and Vibration Bulletin 35, Part 5, 1966.

Sharpe, W.N., Jr.; Kusza, T.J.; Sherman, F.W., and Goff, J.C., Preliminary Measurement and Analysis of The Vibration Environment of Common Motor Carriers, Shock and Vibration Bulletin 44, Part 4, 1974

Singh, S.P., and Young, D.E., Measurement and Analysis Techniques Used to Simulate the Shipping Environments. Presented at the Winter Meeting, American Society of Mechanical Engineers, 1988.

Tevelow, F.L., The Military Logistical Transportation Vibration Environment: Its Charaterization and Relevance to MIL- STD Fuze Vibration Testing, U.S. Army Electronics Research and Development Command, Harry Dimond Laboratories, 1983.

Thomsom, W.T., Theory of Vibration With Application, 3rd. Ed., Prentice Hall, 1988.

Tusyin, W., and Mercado, R., Random Vibration in Perspective., 1984.