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SHOCK AND VIBRATION IN THE RAIL ENVIRONMENT:

TRAILER-ON-FLAT CAR AND CONTAINER-IN-WELL CAR

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Daniel Lee Goodwin

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Larry J. Segerlind
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SHOCK AND VIBRATION IN THE RAIL ENVIRONMENT:
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By

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ABSTRACT

SHOCK AND VIBRATION IN THE RAIL ENVIRONMENT: TRAILER-ON-FLAT CAR AND CONTAINER-IN-WELL CAR

By

Daniel Lee Goodwin

The purpose of this study was to measure the shock and vibration characteristics of the intermodal rail shipping environment. This included trailer-on-flatcar and container-in-well car. Data obtained was to form the basis for a laboratory simulation which could be used as a preshipment test for product and package systems.

A test method was developed to measure the dynamics of the two rail environments. Shocks and vibrations were recorded, in all three axes, for an intermodal distribution cycle from Rochester, NY to Los Angeles, CA. Unattended instrumentation gathered the rail data. Vibration input was processed in a spectrum analyzer and represented as Power Spectral Density (PSD) profiles. The recorded shocks were classified by range and distribution for each axis.

Power Density maximums were found to be 1.5×10^{-4} g^2/Hz, for TOFC, and occurred in the lateral axis. For CIWC the maximum was found in the vertical axis and had a value of 7×10^{-5} g^2/Hz. Since transient shocks increased the vibration responses of the vehicles, the test was to include both dynamic inputs.

For TOFC measurements, 76% of the shocks were in the 2 to 5 g range, in the vertical axis forward location. The vertical rear experienced 50% of the inputs between 4 and 6 g's. In the longitudinal direction 75% of the impacts were in the 0 to 2 g range. Fifty percent of the lateral shocks were seen from 11 to 12 g's. In the CIWC format, 83% of the inputs were from 2 to 3 g's at the vertical forward location, and 75% were in the 2 to 7 g range for the vertical rear. Thirteen percent of the longitudinal shocks fell between 1 and 4 g's, and 20% from 7 to 10 g's. Forty-four percent were in the 15 to 20 g range and 79% of all lateral shocks were measured from 6 to 13 g's.

A digital control system was used to combine shocks with vibration on an electrohydraulic shaker in the laboratory. The test was used as a means of evaluating pallet load stability.

To Latty, Correy and Eric

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Mr. Ronald Holland has been an invaluable friend and ally as the various obstacles and set-backs of data collection were met and overcome. Gratitude is also expressed to Dr. Russel Cain for his insight and suggestions for dealing with the frustrations of original research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure		Page

CHAPTER ONE

INTRODUCTION

Deregulation of the railroads in the United States, brought about by the Staggers Act, 1980, has led to an increase in their share of the common carrier market. Grimm and Smith (1986) have noted increased service quality and management performance, since passage of the act. Two modes of rail shipment have shown significant profitability. These modes are trailer-on-flat car (TOFC), and container-in-well car (CIWC).

Advantages to the firms shipping via these modes include: the elimination of car humping, the most severe load handling hazard in the rail environment; products shipped in trailer-load or container-load quantities will not go through interim loading and unloading operations; and line-haul trains give express service which can be traced through the distribution channel on a mile-by-mile basis.

Flint (1986) observed that rail companies have utilized market pricing, decreased the number of employees, and computerized their operations in their move to recapture market share from the trucking firms. Currently railroads carry 12% of the nation's goods, which is down from the 1962 level of 20%. However, market share for rail is increasing in some areas and is already strong in some others. Trains carry a large share of some product categories: 67% of coal, grain and automobiles; 50% of household appliances; and 50% of food.

Immediately after World War II, 1.4 million people operated the railroads in the United States. In 1986, the same industry carried 35% more tonnage, with only 300,000 workers. Through huge capital investments, more sensible work rules, mergers, and abandonment of unprofitable track, one worker today does the work that once took six to do.

Wesselman (1986) states that productivity has also increased through the introduction of new rail technology. Double-stacking containers in well cars offers a significant economy of scale. Twice the cargo is carried at only 60% of the fuel cost of equivalent TOFC shipments. Even factoring in non-line-haul cost components, such as door-to-door service, leaves a 20 to 25% savings to apply to profits.

Flint (1986) demonstrates the profitability for rail carriers through the comparison of the Dow Jones Industrial Average, which has gone up 80% over the last decade, to the Standard and Poor's Index of railroad stock which is up

200% for the same period. In the same study, Mr. Drew Lewis, CEO for the Union Pacific Railroad states, "The break-even point for CIWC is very high, and the profitability after break-even is so inelastic, it's almost straight up. ..., a 25% increase in volume would more than double our profits."

Computerization has allowed trailer/container volume to be used more efficiently. Flint (1986) cites the example of the Chesapeake Seaboard Express (CSX) which began operating the Orange Blossom Special in 1982. This is a fast run from Florida to New England to try and win northbound fruit and vegetable traffic from the trucking lines. The Special now holds 8 to 9% of the market and is near break-even. Effective volume control as well as competitive pricing has started to increase railroad market share across the country. The Union Pacific Railroad may change freight rates for fruits and vegetables three or four times a day.

Wesselman (1986) compares the various rail and trucking modes and ranks the price advantage of each. Containerization, which includes CIWC, offers the best rate of return for shipments over 1,000 miles. TOFC is most cost effective for distances of 500 to 1,000 miles. Over-the-road truck fares best for distances less than 500 miles.

Manufacturers have found the value of goods contained in a single trailer/container has increased significantly in recent years. Preshipment testing of products, packages and their components, and product/package systems has become common practice throughout most of the manufacturing sector. Through these tests, companies can identify design flaws in products or packages and take appropriate steps to correct them. Test levels and durations are often based on characteristics of the shipping environment. It is also important to know the basic dynamics of product and/or package systems.

Kane (1986) states that intermodal rail shipping methods are relatively new. TOFC has been in common use since the 1960's. CIWC was pioneered by Sea-Land Services in the 1970's. Since there is limited data on these environments, manufacturers have been interested in learning the nature and level of the shock and vibration dynamics. As will be discussed in Chapter Two, few studies have been published on TOFC or CIWC formats. The data which has been published is primarily for short runs of 200 to 500 miles, and was gathered on experimental trains that do not reflect actual use conditions. Profitability of the aforementioned rail modes is based on shipping distances of <u>at least</u> 500 miles.

Kane (1986) finds double-stack trains (CIWC) offer more versatility for load carrying formats. They can carry 20 and 40-foot containers, each 8 ft. 6 in. high, as well as the newer 45-foot units, which are 9 ft. 6 in. high. Labor inputs are significantly reduced through double-stacking practices. If a double stack train hauls 200 containers across the country in five days, only four or five workers are needed. To move the same volume by truck, in the same time period, would require 400 drivers.

Considering the fact that there have been technological innovations in the physical characteristics of the railways, railcars, and handling systems, TOFC and CIWC shipping modes should be evaluated. Advances have also been made in data gathering and analyzing equipment. Such advances have broadened the capabilities of laboratory test equipment to simulate shipping environment dynamics.

1.1 OBJECTIVE

The objective of this study was to measure the shock events and vibration inputs to a 40-foot container filled with 43,000 lbs. of chemicals and photographic materials. This container traveled from Rochester, NY to Chicago, IL on a trailer chassis, as part of a TOFC shipment. In Chicago, the container was transferred to a double-stack well car and transported to Los Angeles, CA. The data collection procedures were to utilize unattended instrumentation techniques. Both shock and vibration events were to be measured in all three axes. The shock and vibration data was to be used to create a laboratory test procedure which would simulate the intermodal rail shipping environment.

CHAPTER TWO

LITERATURE REVIEW

There are a number of factors that must be considered with respect to the need for studying the TOFC and CIWC distribution environments. Review of published environmental studies revealed little data for the double-stacked container in a well car format. Based on information discussed previously on the profitability of this mode of shipment, it is clear its usage is likely to increase. Trains utilizing either TOFC or CIWC modes are not coupled by ramming one car into another. Some TOFC shipments are made up in the rail yard by straddle cranes, which lift the trailers and place them on flatcars that are already coupled. Others utilize ramps to back trailers onto flatcar platforms. CIWC units are also already coupled when devices such as Santa Fe's port packers, double-stack the containers. See Figures 2-1 and 2-2.

Shippers find there will be no interim handling of cargo en route. In line-haul transport, cars will not be added or removed from the train, nor will their lading be unloaded and placed in other cars. Since the routes are determined in advance, it is possible to track the cargo through the

Figure 2-1. Straddle crane.

Figure 2-2. Container stacking.

entire distribution system. This is an advantage for determining the locations of various dynamic inputs which are experienced during the journey.

Published studies on the TOFC environment are, for the most part, measurements of experimental trains. The study by Kenworthy (1979), for the Department of Transportion, is an example. Such tests involve a locomotive, test cars, buffer cars and an instrumentation car. In addition, the runs are relatively short distances of 200 to 500 miles.

Well car design offers a means to reduce some of the dynamics experienced in conventional flatcar formats. Longitudinal slack action is reduced through use of an articulated coupling. This is shown in Figure 2-3. Figure 2-4 shows the five platform configuration for these cars. Each end of the unit has a standard coupling, but the intermediate couplings are fashioned with pins and provide a fixed, rigid connection. This technique minimizes the "run-out" and "run-in" as the train speeds up, slows down or goes up and down hills. The benefits of the new well car designs were described in the July 14, 1986 issue of Pacific Shipper, in an article entitled, "APC Dramatizes Stack Train's Smooth Ride by Carrying Table-for-Two With China."

The above article also found that horizontal stability is enhanced through the use of side bearings in the truck

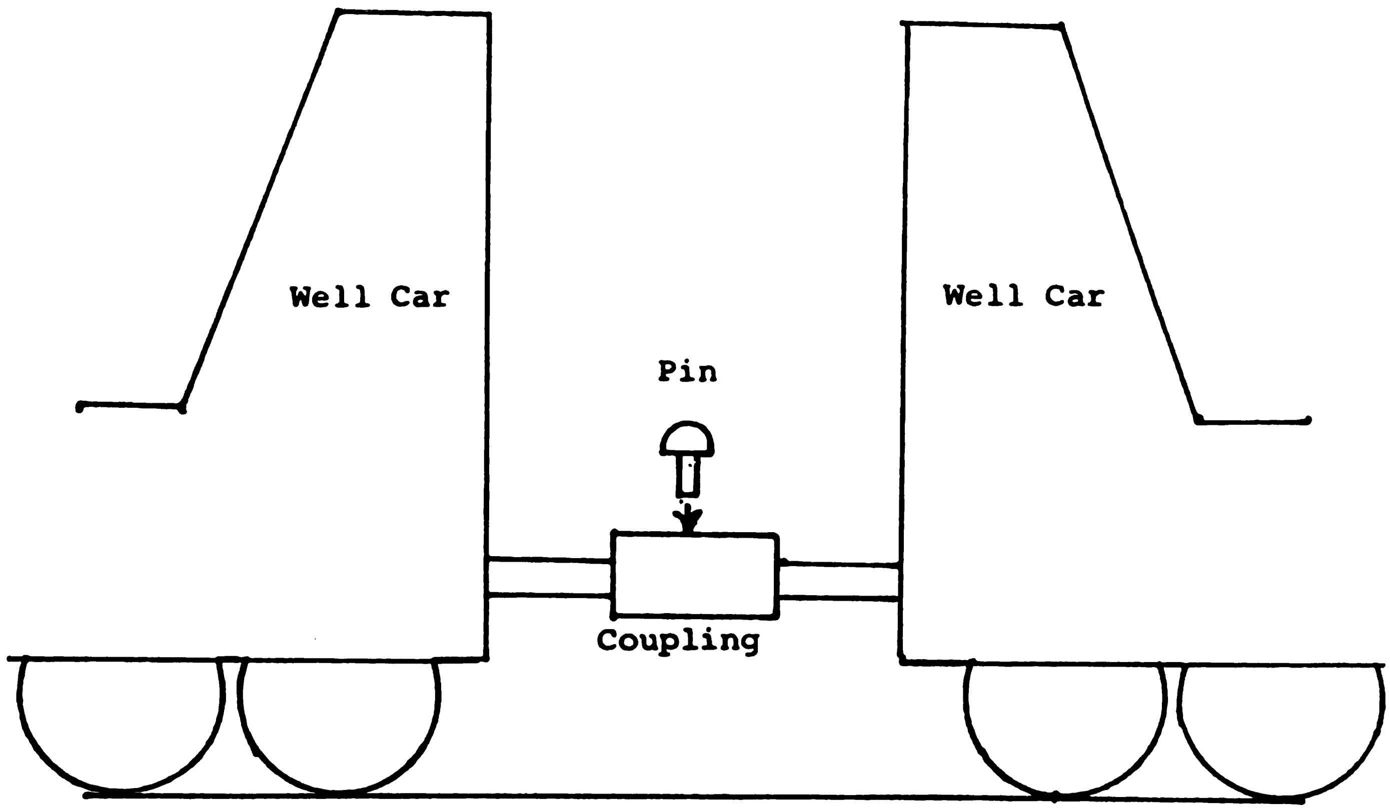


Figure 2-3. Articulated coupling.

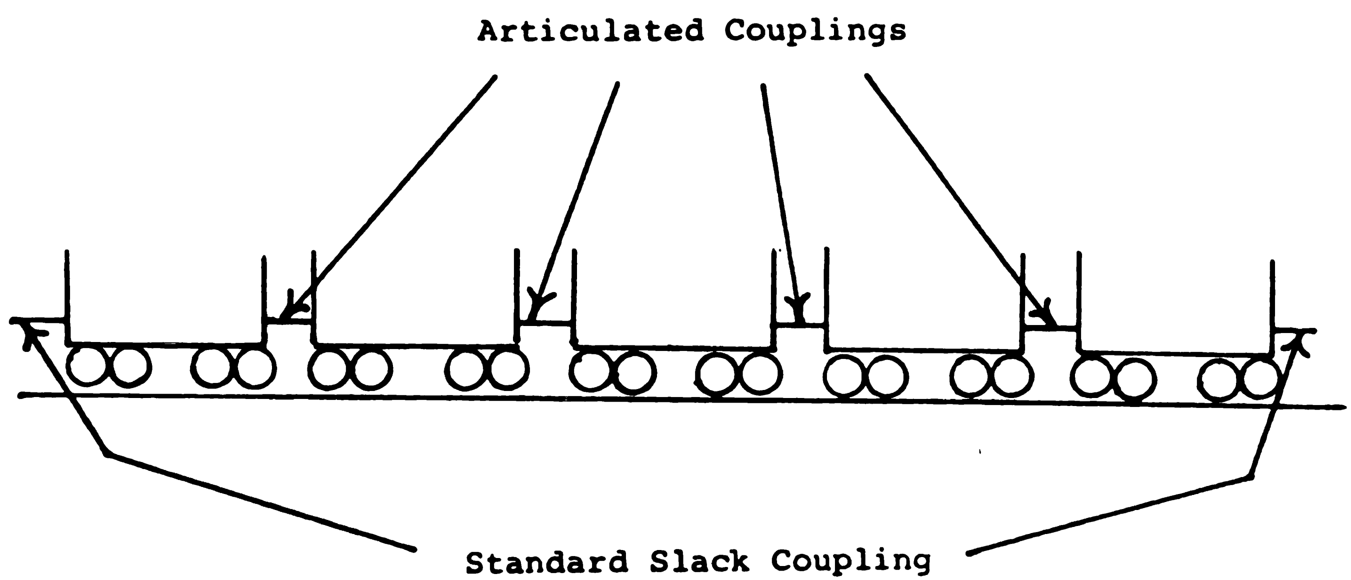


Figure 2-4. Five-platform format for well cars.

assemblies. Vertical vibrations are minimized by reducing the distance between truck centers on each platform, as shown in Figure 2-5.

In addition to the above, the well car design adds stability and provides a lower center of gravity, as can be seen in Figure 2-6. This reduces side-sway. APC has experienced significantly reduced damage levels in the well cars. Standard flatcars regularly encounter vertical accelerations of 1.7 g's and longitudinal forces of 2 g's. The well car design keeps both levels below 0.2 g's. These facts are reported in the American President Company study of July, 1987.

Shippers who rely on preshipment testing of products and product/package systems attempt to anticipate or recreate damage seen in the field. In such cases, the worst possible hazards are used in determining test levels. The basis for many of the common test procedures is found through measurement of field parameters. Since the early 1970's, several procedures for random vibration testing have relied on Power Spectral Density profiles to identify the energy at various frequencies. Hanes (1983) measured the environmental dynamics for both over-the-road truck and padded van, and developed random vibration tests for IBM, that replaced existing sine-dwell methods. However, there is still some inconsistency regarding the methods for reporting vibration data.

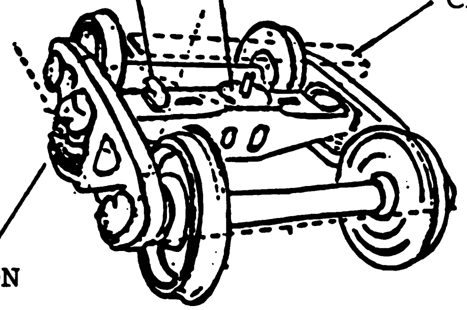


Figure 2-5. Side bearing minimizes lateral movement.

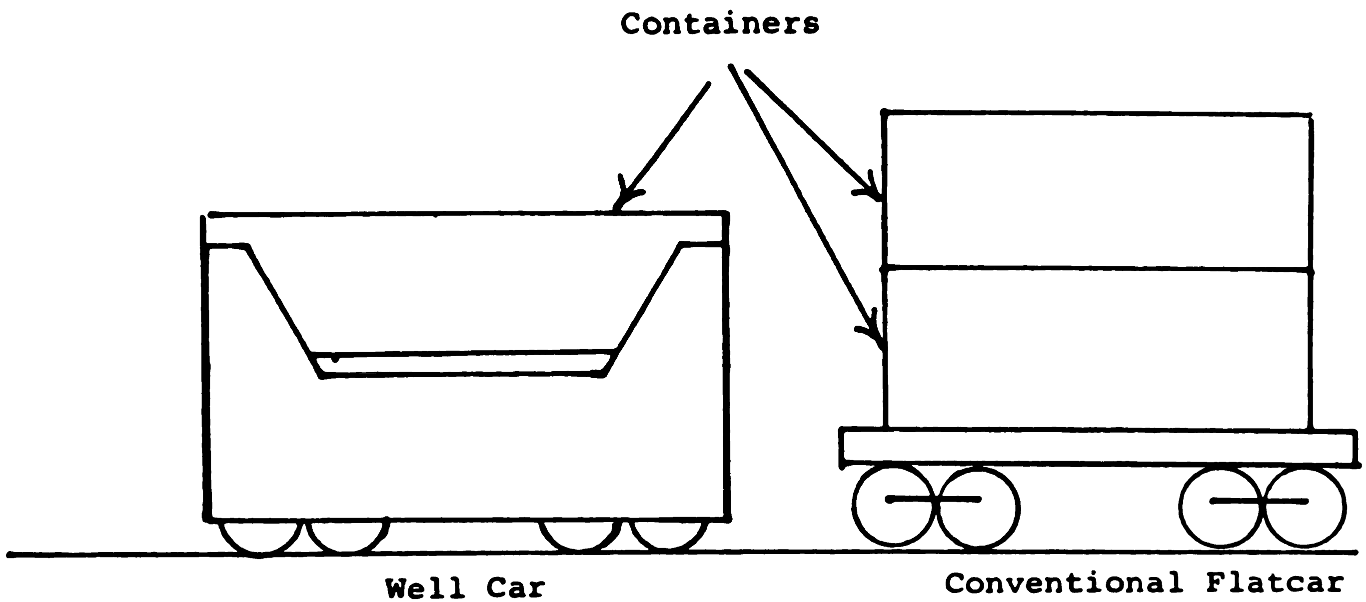


Figure 2-6. Comparison of well car and flatcar.

Random vibration data is converted to Power Spectral Density (PSD) profiles through the use of spectrum analyzers, which perform Fast Fourier Transform operations on the raw information.

The equation for determining Power Density is:

$$PD = \frac{\sum_{i=0}^{i=N} (RMS)_i^2 / N}{BW} \; g^2/Hz \qquad (2.1)$$

PD = Power Density (g^2/Hz)
RMS = Root Mean Square acceleration (g's)
N = Number of data samples averaged
BW = Bandwidth of the filter (Hz)
(usually normalized to 1 Hz).

See Appendix B for a complete discussion. When this method of data processing is completed, the PSD profiles become the test profile. However, transient shocks occurring in the environment are averaged out through the data manipulation. It will be shown that transients, superimposed on the random vibration profile, add significantly to the dynamics of the system response.

The use of digital control vibration systems has made it possible to program these shocks back into the random vibration input. Also, the advent of electrohydraulic shaker systems, with multiple degrees of freedom, makes it possible to input forces from all three axes, simultaneously.

Accuracy of data collection has improved with the capability of measuring vibration input down to nearly DC level, or 0 Hz. Low-end frequencies are important to consider in developing test profiles, due to the large displacements that occur in these ranges, as a result of input from vehicle suspension systems. This was reported by Schlue and Phelps (1968).

The common carrier shipping environment can be defined as including all conditions likely to be encountered by products moving from point of manufacture, or harvest, to the final consumer. Various vehicular transportation modes, handling, and storage activities are associated with this process.

Previous studies have reported data and descriptions of the environments in a variety of different formats. This variation is due to the types of instrumentation available, data reduction systems and the type of end-use concerned. The following discussion will address the nature of test procedures used for collecting data and the levels of the dynamics encountered.

Ostrem and Godshall (1979) reported an overview of the common carrier shipping environment. The characteristics of the vibration environment have been studied in greater detail than any other shipping hazard. Reasons for this include: shippers have little control over the operation of commercial vehicles and the resulting vibrations transmitted to the lading; vibration measurement requires sophisticated equipment so testing is usually precise and detailed; and access is often not available to the carriers' vehicles.

Forms of reporting the data include: Power Spectral Density (PSD) plots; Root Mean Square (RMS) Accelerations; RMS versus Frequency; Peak Acceleration versus Frequency; and Distribution of peaks within given frequency ranges. Acceleration levels reported are dependent on the bandwidths of the filters used for data analysis. These filters separate the complex signals into discrete frequency bands. Ostrem and Godshall (1979) indicated that current technology relies on constant bandwidth filters used in compression real-time analyzers (RTA) and Fast Fourier Transform (FFT) analyzers. Both analyzers produce the same results. Samples of amplitude-time histories are analyzed to produce amplitude-frequency spectra at a rate dependent on the frequency resolution needed. The various spectra are then combined to generate an averaged spectrum. Current analysis typically relies on 1-hertz bandwidths and presents data in the form of PSD levels in units of

g^2 /Hz. This is considered to be the only format suitable for describing random vibration. It is used as both a test specification and an analytical parameter.

2.1 VIBRATION IN COMMON CARRIER VEHICLES

The following section discusses the results of vibration studies on trucks and railcars. Both have implications for TOFC and CIWC investigations.

2.1.1 Over-The-Road Truck

Figure 2-7 shows a typical series of vibration profiles for over-the-road trucks, plotting peak acceleration against frequency. Such data indicates that probabilities can be used to compare the levels of severity for a given vehicle. The advantage of the statistical format is in identifying the distribution of acceleration below the peaks. However, a large data base is needed to produce that summary.

Schlue (1966) reports finding peak PSD levels at 2, 10, 11, and 50 Hz in truck trailers. The low-end frequencies were determined to reflect input from the suspension system. The 50-hertz peak was identified as a structural response. Such structural responses were found to contain little energy.

Kusza and Sharpe (1973) found the vibration levels at the vertical rear location, over the rear wheels, to be the

Source: Forest Products Laboratory

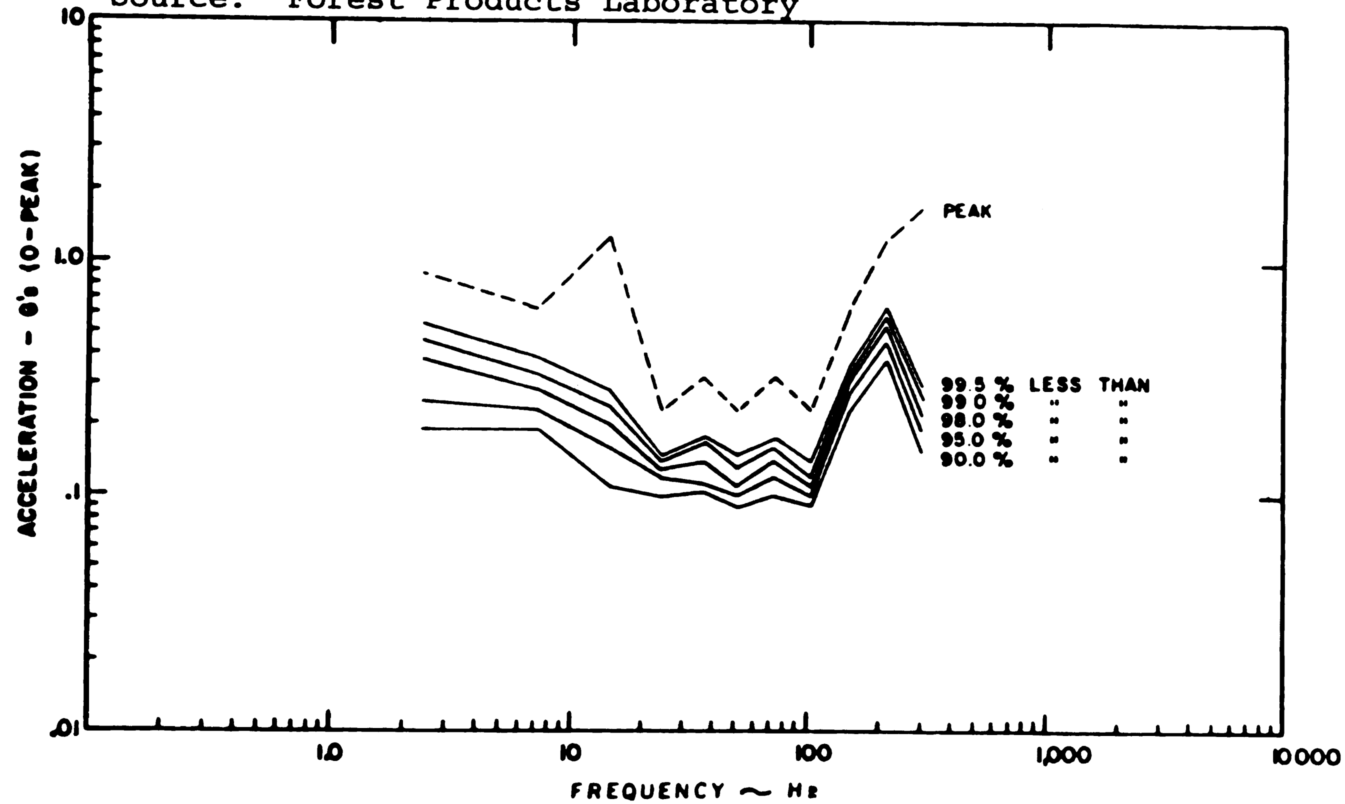


Figure 2-7. Frequency spectra for truck (vertical).

most severe. Mid-trailer points were the least active, and the forward area, over the king-pin, was in-between. Lateral acceleration motion was half that of vertical input. Speed increased the amplitude of vibration, but did not change the frequency profile.

Silvers and Caruso (1976) report that the worst case for shipping is to place cargo directly over the rear wheels of a lightly loaded trailer. With regard to road type, high speed highways generated the highest amplitude levels.

In Figure 2-8, the PSD profiles for the above three studies are compared. The levels of peak acceleration are roughly equal, but differ as to the related frequencies. They show the variation in vehicle and load combinations. A conservative test profile could be defined by enveloping the peaks in a straight line giving a constant PSD. This is shown in Figure 2-9. The peaks and notches do exist, however, and should be included in the test profiles since it could potentially reduce overpackaging.

Random test procedures, such as ASTM D-4728 (1987), indicate that PSD plots are an effective format for carrying out the data analysis and test design. However, package-related applications are better served by descriptions of acceleration and frequency levels. This is because transmissability characteristics of cushioning

Source: Forest Products Laboratory

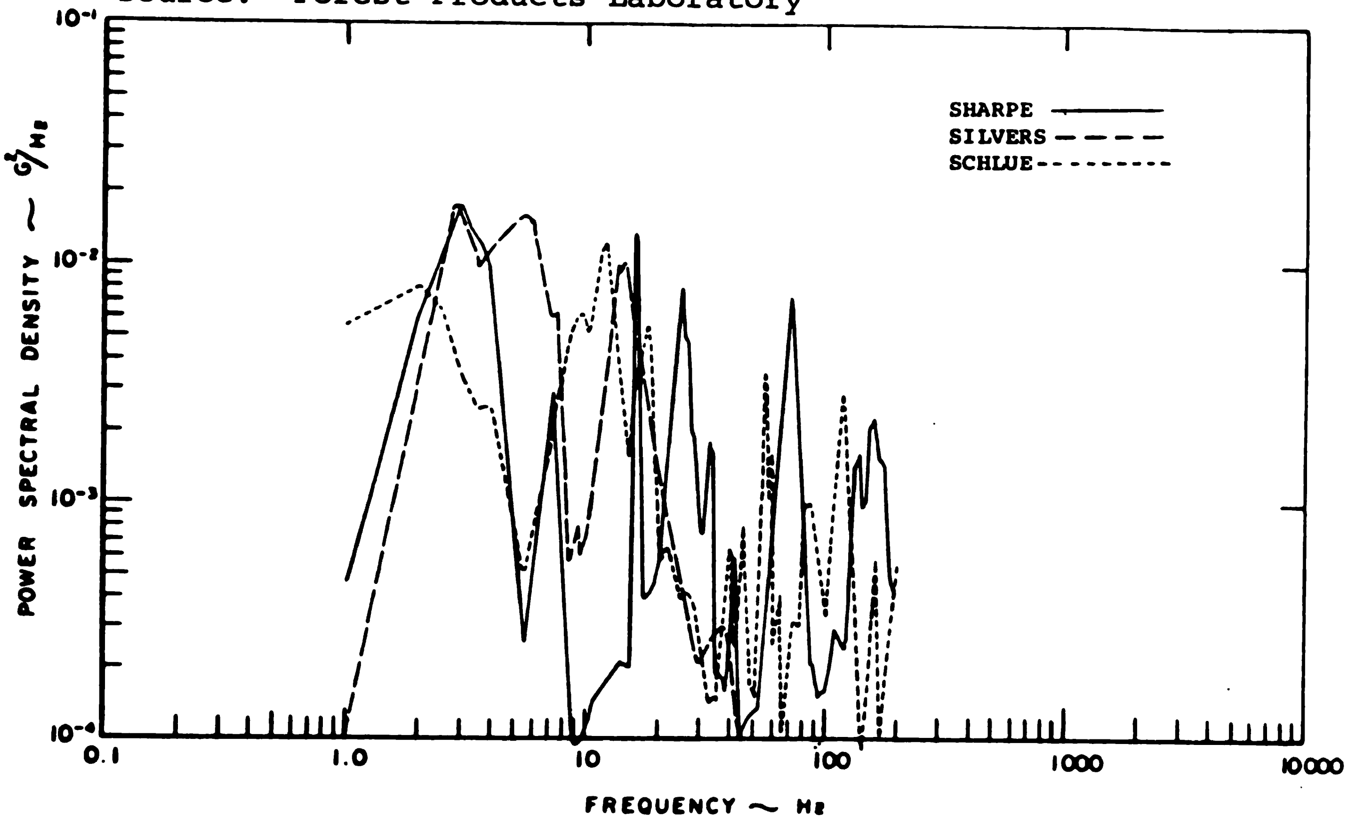


Figure 2-8. Truck frequency spectra - summary of PSD data.

Source: Forest Products Laboratory

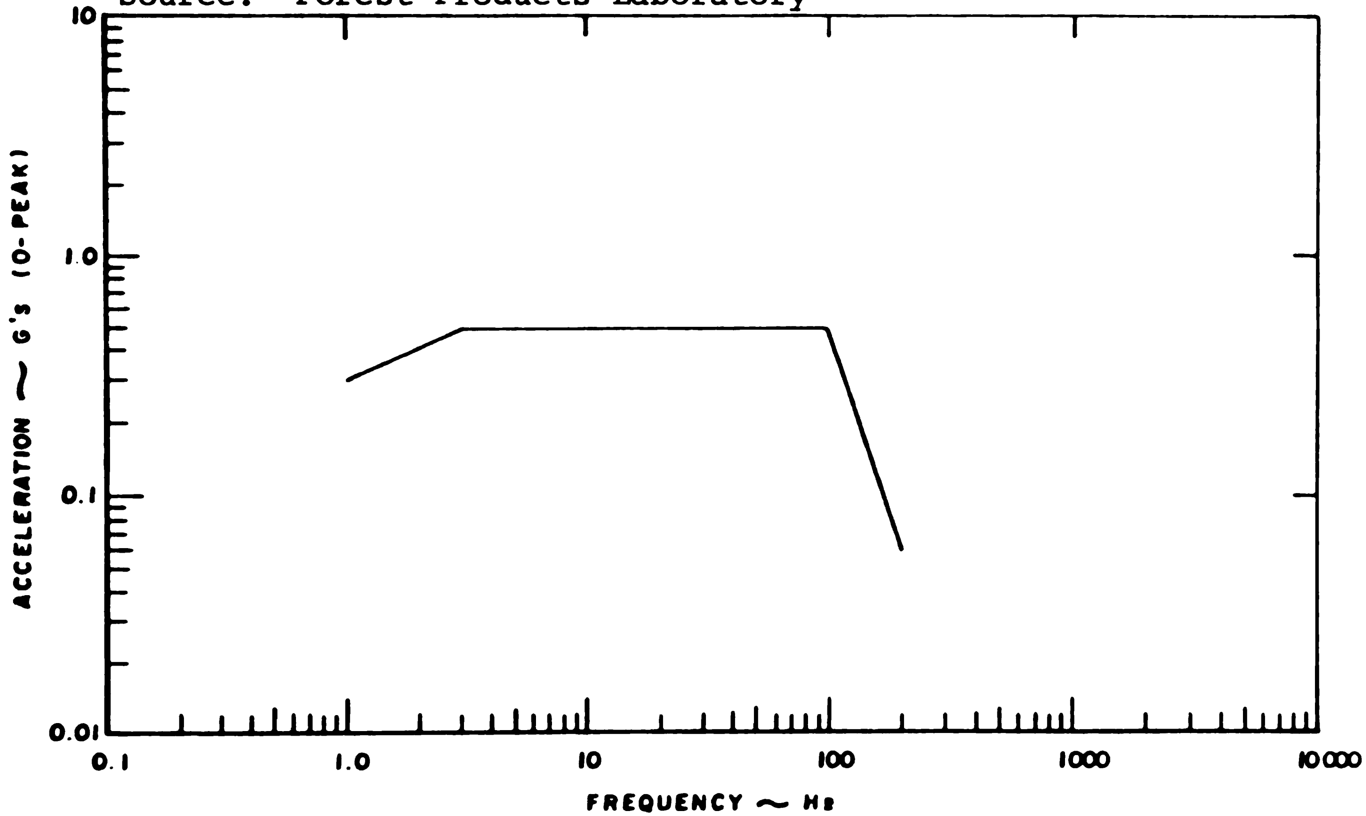


Figure 2-9. Vibration envelope curve - truck summary.

materials are defined with respect to the natural frequency of the cushion under load.

Cargo placement has been shown to influence the measurement of trailer floor dynamics. This is particularly noticeable with light loads of loose cargo and cargo in resonance. It has been shown that cargo may not respond to some inputs due to natural damping conditions. Silvers and Caruso (1976) address this issue for light loads by removing the cargo and reporting the severest environment as the empty truck. This eliminates the effects of bouncing loose cargo.

Ostrem and Godshall (1979) discuss some of the inconsistencies in the reporting of resonant frequencies found in trucks. They cite the most significant differences as occurring in the frequency range above 50-hertz. The most likely cause for this is poorly maintained or functioning suspension systems.

2.1.2 Rail Cars

Ostrem and Godshall (1979) observed that past studies on railcars focussed much attention on the periodic input from rail joints. These joints occurred every 19.5 feet, alternately on both left and right rails, because the standard rails were 39 feet long (Figure 2-10). The car's geometry generates periodic input also, with respect to the

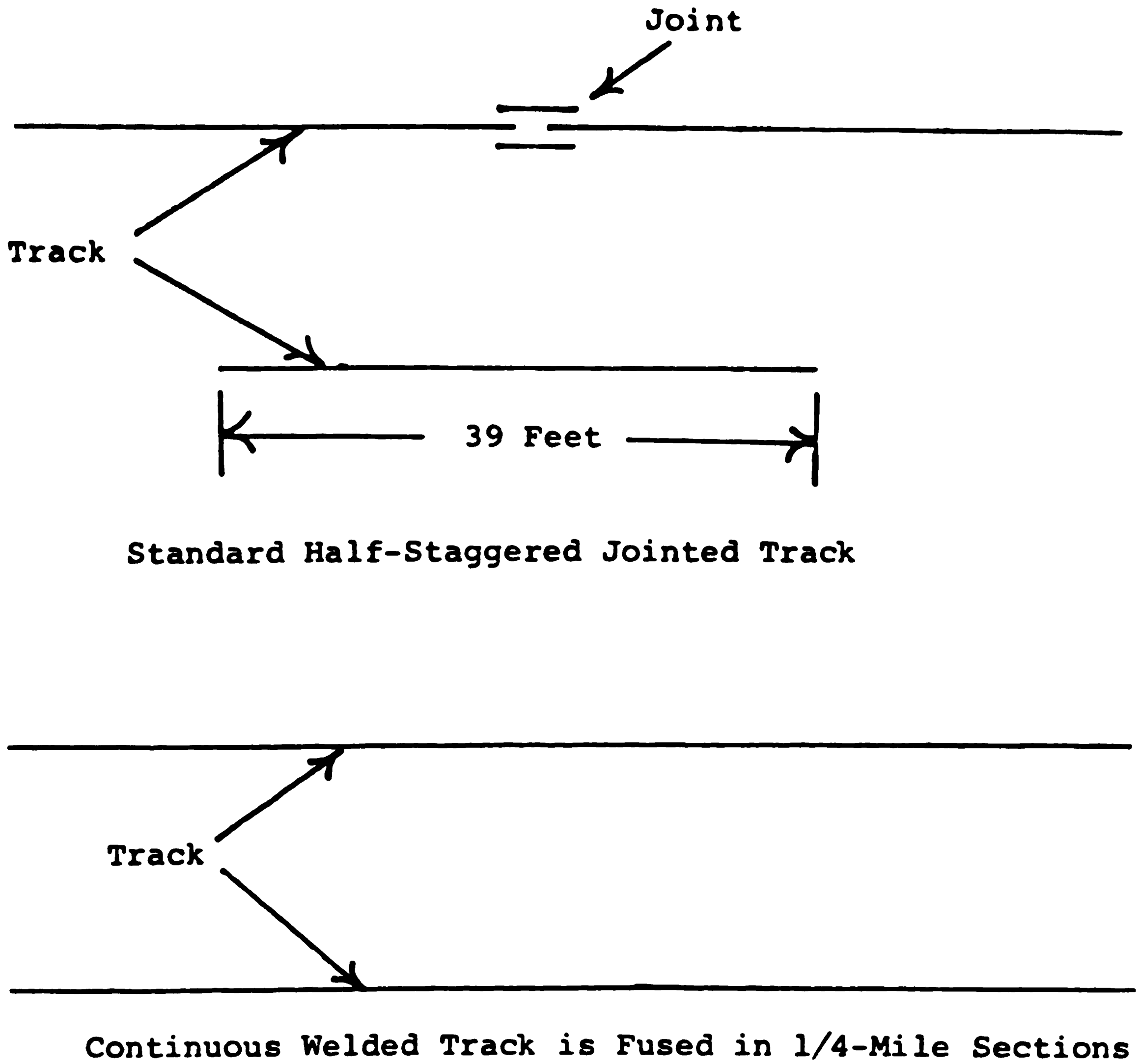


Figure 2-10. Track comparisons.

joints. The overall axle wheelbase distance, the interior wheelbase distance, the truck centerplate distance, and the truck axle wheelbase all determine the periodic inputs to the car. Inputs may also come from eccentric wheels or flat spots on wheels.

Large responses occur while any of the forcing frequencies are the same as those within the railcar system. These include low-speed rolling or rocking and the effects of wheel lift-off. Frequencies causing the above are typically below 20 Hz for train speeds up to 75 mph.

Continuously welded track has eliminated periodic input from rail joints, but the unevenness and roughness of the rail system still cause significant vibrations to occur. Responses of the railcar to irregularities on welded track are at system natural frequencies of the car truck and track. Vertical inputs also come from rail intersections and road crossings in the form of transient loadings. These will cause the car to vibrate at its natural frequencies.

A study by Sharpe (1972) indicated major peaks in a Hy-Cube, 70-foot, 100-ton boxcar, loaded with 30 tons of scrap iron, occurred at frequencies of 20, 40, 60, 80, 120 and 400 Hz, with the maximum peak observed at 60 Hz. These peaks remained even though the speed was varied and the suspension altered. This would indicate the responses are a function of the car body natural frequencies, and are excited by impulsive loadings at the interface of the wheel and rail. It was also found that increased speed resulted in increased levels of vibration and vibration on welded track was lower than jointed track. Welded track essentially eliminated the peaks. Welded track PSD data appear very similar to wide-band random vibration.

Guins (1974) reported very little response above 15 Hz in the preliminary report on a 5,000 mile test conducted by the Association of American Railroads. Most of the significant peaks were below 10 Hz.

Foley (1972) describes frequencies below 10 Hz as the result of transient impulses. Byrne and Anderson (1976) observed "truck hunting," lateral instability within the flatcar, occurs between 40 to 50 mph for half-staggered, jointed track, and above 50 mph for continuous welded track. Major peaks in the vertical axis related to rail joint frequencies, while secondary inputs related to truck geometry. All inputs were below 6 Hz.

A comparison of the above rail car studies show an order of magnitude reduction in PSD levels when compared with over-the-road trucks. Scarcity of data requires more rail testing, especially in the low frequency range from 0 to 10

Hz. Summary of the above information shows conventional railcars have a maximum PSD level of 10^{-3} g^2/Hz. See Figure 2-11. Figure 2-12 shows an envelope curve which summarizes the peak accelerations measured in railcars. By using only peaks, a conservative profile is defined. Figure 2-13 shows a composite of various rail frequency spectra. Measured frequencies occurred in the vertical axis, and are profiled as percentages of peak accelerations. A direct relationship has not been found between the effects on lading of a constant amplitude sinusoidal vibration and random vibration.

2.2 Shock Inputs

One difficulty in analyzing shock data as an environmental parameter is that it must be separated from vibration data and treated accordingly. Shock events were not always defined in the same way by the various investigators. Some events were classed as a vibration input in one study and a transient shock in another.

Shocks have been measured on both the lading and the lading floor, in various vehicles. Inputs to lading are generally reported as peak accelerations and those inputs to the lading floor are presented as peak accelerations, shock spectrum or spectral analysis.

Data reported as peak lading acceleration has several advantages, since it can be directly related to product

Source: Forest Products Laboratory

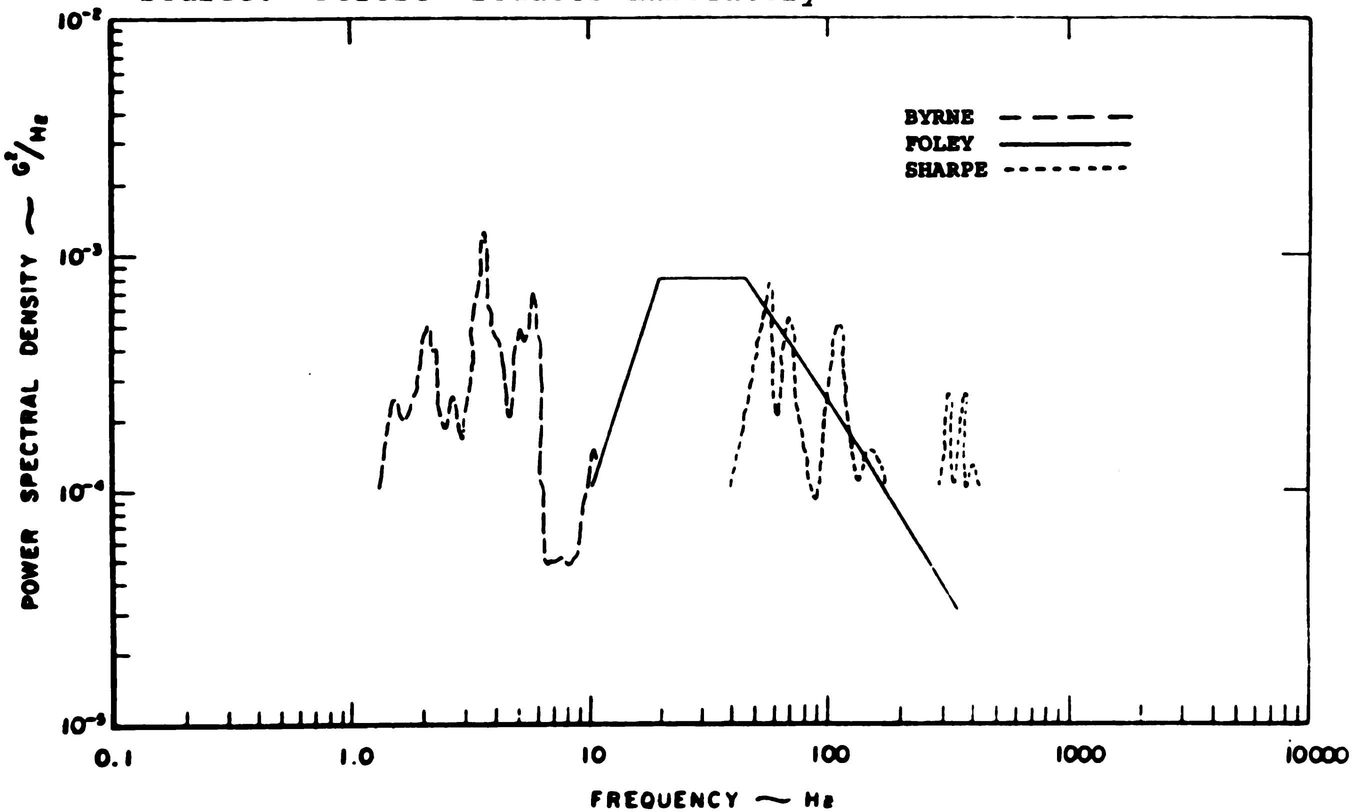


Figure 2-11. Railcar frequency spectra - summary of PSD data.

Source: Forest Products Laboratory

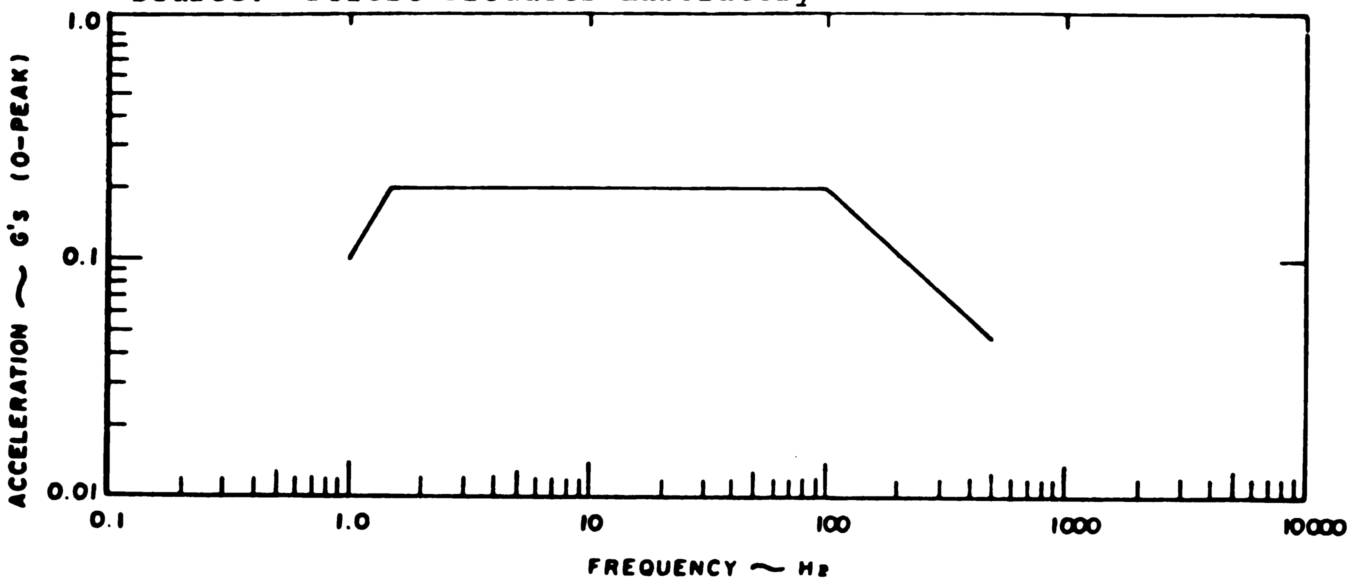


Figure 2-12. Vibration acceleration envelope - railroad.

Source: Forest Products Laboratory

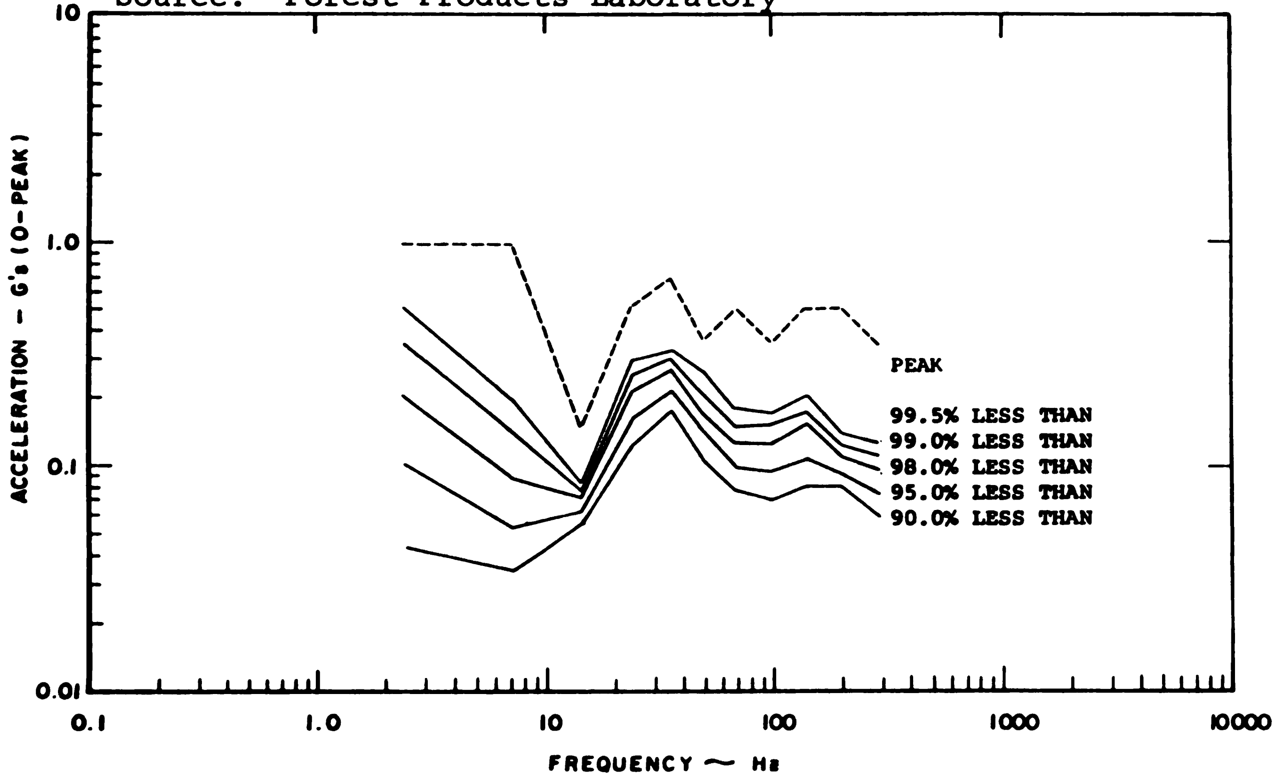


Figure 2-13. Frequency spectra for railroad (vertical).

Source: Forest Products Laboratory

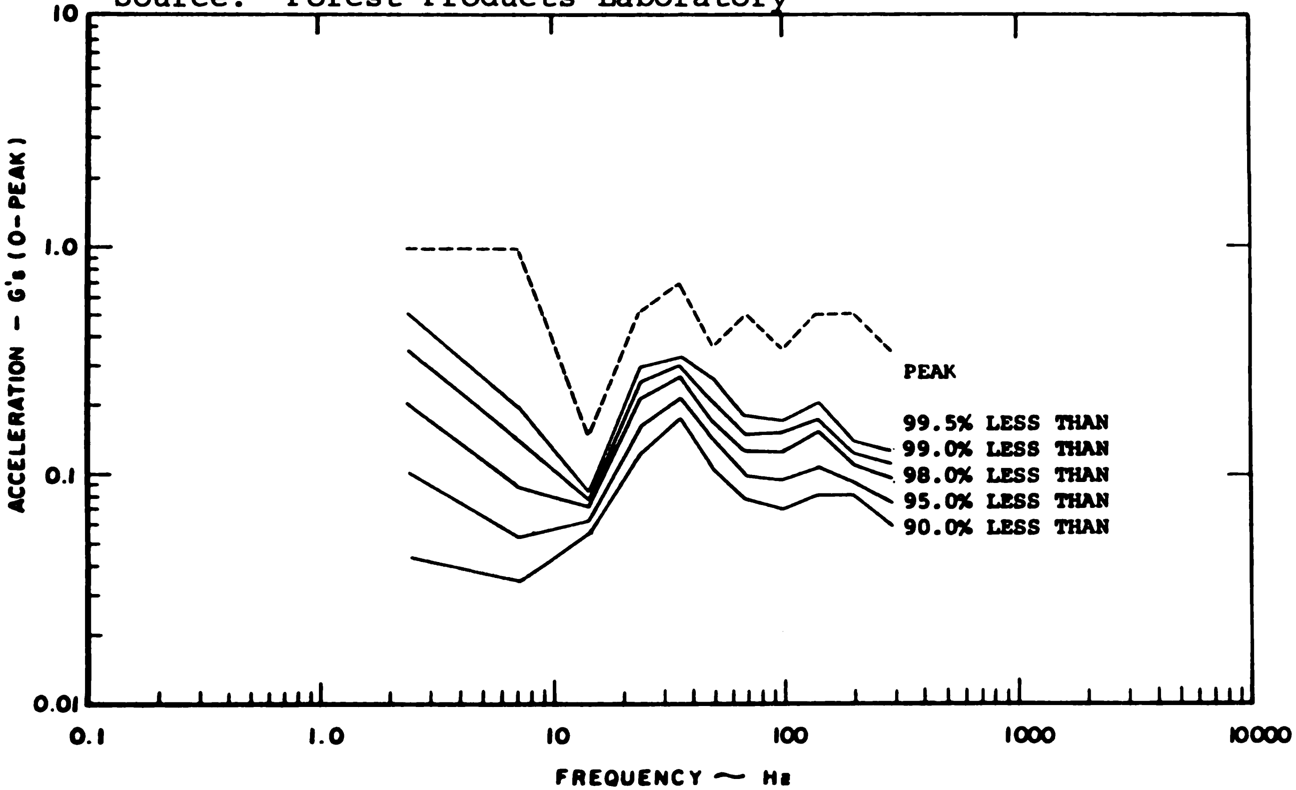


Figure 2-13. Frequency spectra for railroad (vertical).

fragility or "g" rating. The ASTM D-3332 Standard Test Method for Mechanical-Shock Fragility of Products, Using Shock Machines describes the procedure for this test. Packaging engineers can use such data to design appropriate cushioning systems for their products. Appendix A reviews the fragility concept. Measured peak acceleration to the floor of the vehicle is not as useful to package cushion design unless the product is simple and unprotected. More sophisticated studies have translated shock inputs to either shock spectra or peak acceleration versus natural frequency of the responding system. Using this information, the maximum value of the response, at the dominant forcing frequency, due to the input motion at points where cargo is located, can be determined.

Another manner of analyzing shock data is to do a waveform analysis which plots peak acceleration as a function of frequency. It has been suggested by Harris and Crede (1976) that most transients in the distribution environment could be simulated with a random vibration generator.

Some method of marking transients is required to separate them from continuous input such as random vibration, if recorded on the same instrument. Rail cars experience vertical transients when cars cross intersecting track, switch junctions, roadways or bridges. Longitudinal inputs occur during switching or coupling operations. No humping occurs with loaded flatcars (TOFC) or well cars (CIWC). Run-ins and run-outs do occur, longitudinally, with the above, and were measured as transients.

Studies on commercial trucks have indicated that transients produce increased low-frequency vibration and <u>not</u> sharp peaks. The general level of peak accelerations at given frequencies are much higher during a transient event. Kusza and Sharpe (1973) report levels of 2.7 and 5.0 g's for a truck crossing an expansion joint and road intersection, respectively. They also conclude that if a random noise generator is used to produce a test signal, these higher levels will be produced automatically.

Johnson (1971) found that impact pulse shapes for heavier packages, reported in truck studies, were nearly half-sinusoidal, with durations of 3 to 5 ms, for more than 90% of the events recorded. These packages also showed lower accelerations. Weights ranged from 50 to 2,200 lbs.

Sharpe's (1972) data for rail crossings showed peak accelerations varied from 0.95 to 1.4 g's. Two types of responses were noted. The first demonstrated uniform increase and subsequent decline with time. The other indicated a large initial acceleration followed by a slow return to conditions prior to the event.

Package bounce and repetitive shock can be very damaging. This has been demonstrated by glass breakage studies in Britain. Lee (1969) performed studies using low cost, highly fragile, glass bottles, bulbs and ampoules to rank the severity of transients. The number damaged was used as the scaling factor. Rear overhang areas were the worst positions for cargo and corresponded to equivalent drop heights of six inches or less. Cargo peak accelerations versus the number of occurrences are useful if simulated in the laboratory. Vibration parameters measured on empty trailers may address this issue. However, this investigator was not able to find any correlation studies between empty truck vibration and bouncing packages.

CHAPTER THREE

TEST METHODOLOGY

Trailer/container instrumentation procedures involved the use of eight piezoelectric accelerometers. Four accelerometers measured transient shocks and four measured vibration inputs. The shock and vibration accelerometers were placed, side-by-side, in each of four different locations.

Previous studies completed by Kenworthy (1979), suggested the midpoints of highway trailer floors experienced the least energy when placed on rail flatcars. In order to record the most severe inputs, two vertically mounted accelerometers were placed over the kingpin and the rear wheels along the trailer floor centerline, Figure 3-1.

Placement of accelerometers on vehicle floors was found to vary from study to study. A trailer floor is not a rigid plane. It has various bending modes. In order to identify the characteristics of this response, a modal analysis was performed. Floor resonances were excited and analyzed. Results for a 38-foot truck trailer floor show major resonances fall within the 1 to 12 Hz range. These are

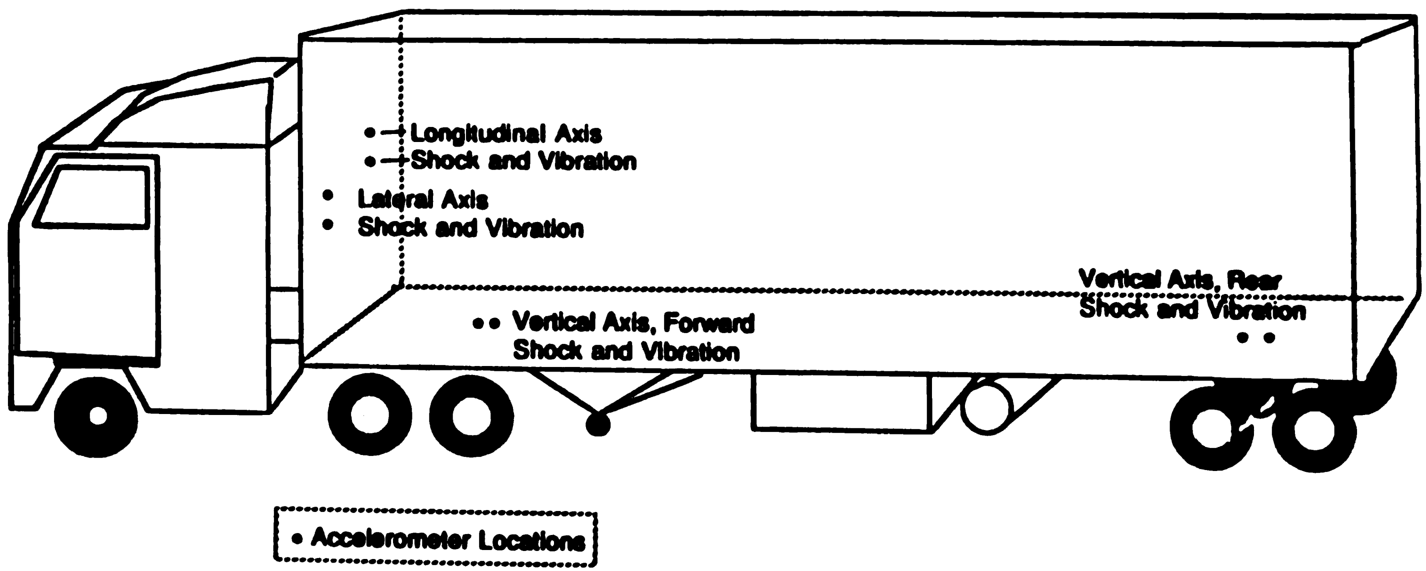


Figure 3-1. Over-the-road truck.

most pronounced over the rear one-third of the floor. See Appendix C for details on these measurements.

The lateral axis was instrumented in the forward left corner of the trailer. The study, referenced above, indicated lateral accelerations of TOFC shipments were 1.5 to 2 times greater at the top than the bottom of the side walls. A mounting height of six feet was chosen, since the single pallet heights were approximately five feet, and this would represent the most severe input cargo would experience.

The longitudinal axis was also instrumented at a height of six feet. Both lateral and longitudinal accelerometers were placed in a corner support column, to minimize the effects that noise from wooden inner panels would have on the readings.

The trailer/container lading in this study was comprised of liquid chemicals and photographic materials. Liquid chemicals were placed in 55-gallon fiber drums and 5-gallon polyethylene bags inside of corrugated shipping containers. Photographic film and paper were also placed in corrugated shipping containers. All pallet loads of product were stretch wrapped for purposes of unitization. The 48 by 40-inch pallets were "pinwheeled," or placed with the 48-inch length staggered, to minimize load shift. Air bags were also used to stabilize the cargo. Protective wooden boxes, 8 by 8 by 2.5 inches, were placed over the accelerometer mounting positions on the floor, as seen in Figure 3-2.

All recording instruments were strapped to the top of the forward-most pallet, as shown in Figure 3-3. The bump recorders were contained in urethane cushioned blocks and the tape recorder was placed in a large plastic container lined with polyethylene foam.

3.1 VIBRATION EQUIPMENT

The device used for recording random vibration inputs was a Bruel and Kjaer (B&K) Model 7007 instrument grade, FM, reel-to-reel tape recorder. The data was stored on a magnetic tape.

In order to tape record portions of the entire trip, the recorder was fitted with a programmable timing module. As seen in Figure 3-4, the module has a series of dip switches that control the frequency and length of recorded segments. Using a tape speed of 38.1 mm/sec., the recorder required nine meters of tape for a four-minute segment. Since the recorder was activated every two hours, approximately 648 meters of tape was used in the six day trip from Rochester, NY to Los Angeles, CA. This programming procedure allowed a 690 meter tape to be used effectively.

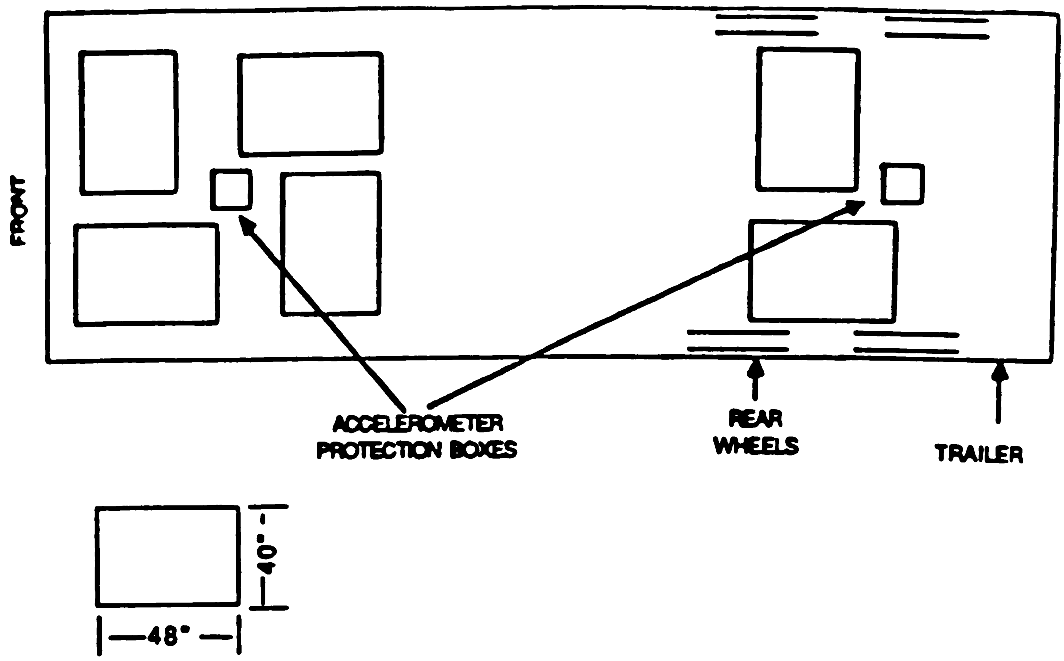


Figure 3-2. Pinwheel pallet loading configuration.

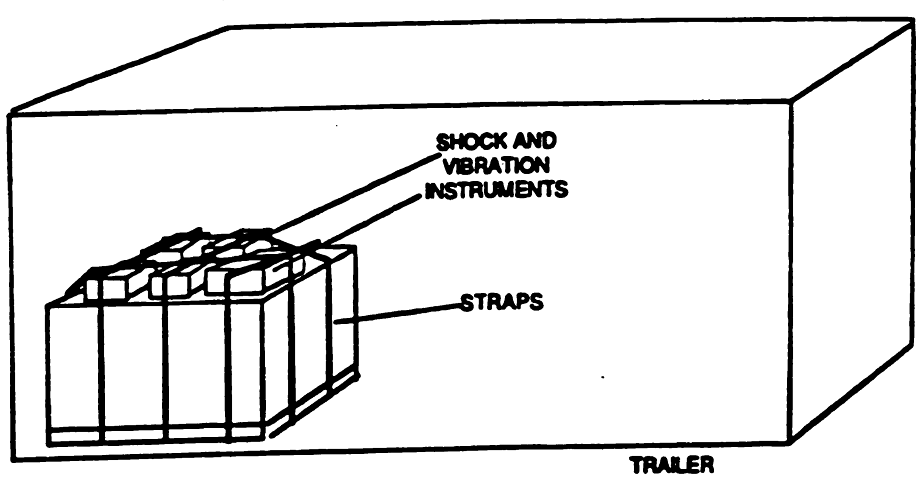
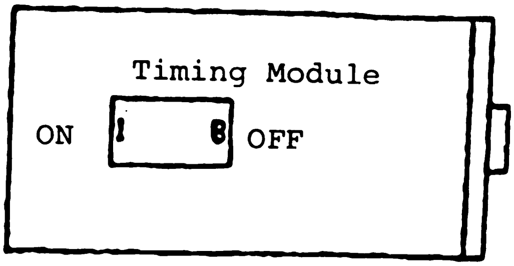


Figure 3-3. Instrument placement and protection.



PERIOD

HOURS \ SWITCH	1	2	3	4
→ 2	0	0	0	0
4	1	0	0	0
6	0	1	0	0
8	1	1	0	0
10	0	0	1	0
12	1	0	1	0
14	0	1	1	0
16	1	1	1	0
18	0	0	0	1
20	1	0	0	1
22	0	1	0	1
24	1	1	0	1
26	0	0	1	1
28	1	0	1	1
30	0	1	1	1
32	1	1	1	1

RECORD

SECONDS \ SWITCH	5	6	7	8
30	0	0	0	0
60	1	0	0	0
90	0	1	0	0
120	1	1	0	0
150	0	0	1	0
180	1	0	1	0
210	0	1	1	0
→ 240	1	1	1	0
270	0	0	0	1
300	1	0	0	1
330	0	1	0	1
360	1	1	0	1
390	0	0	1	1
420	1	0	1	1
450	0	1	1	1
480	1	1	1	1

Figure 3-4. Tape recorder timing module.

The recorder was powered by two 12-volt gelatin batteries, wired in parallel, as shown in Figure 3-5. Based on information from B&K, the range setting for all four of the charge amplifiers was 100 mv/m/sec . This translated to a calibration factor of 3.22 g/volt. The frequency range was 0 to 120 Hz.

3.2 SHOCK INSTRUMENTATION

Shock data was gathered on B&K Model 2503 bump recorders. The four units were individually powered by rechargable nickel-cadmium batteries. The threshold level for a shock event was set at 2 g's. This figure was chosen after preliminary data indicated 1 g would exhaust the tape too soon, and 5 g's would not generate sufficient data.

Analog signals generated by the shock transducers were translated to a paper data tape by a thermal printer. Each tape was capable of recording over 700 events. Events were triggered when a 2 g shock occurred, and ended when the analog signal fell below the threshold for 1 second.

Figure 3-6 shows the entire schematic for the shock and vibration instrumentation. Cables were shielded and used micro-dot connections. The cables were combined into an insulated wiring harness to avoid kinks and abuse during transit.

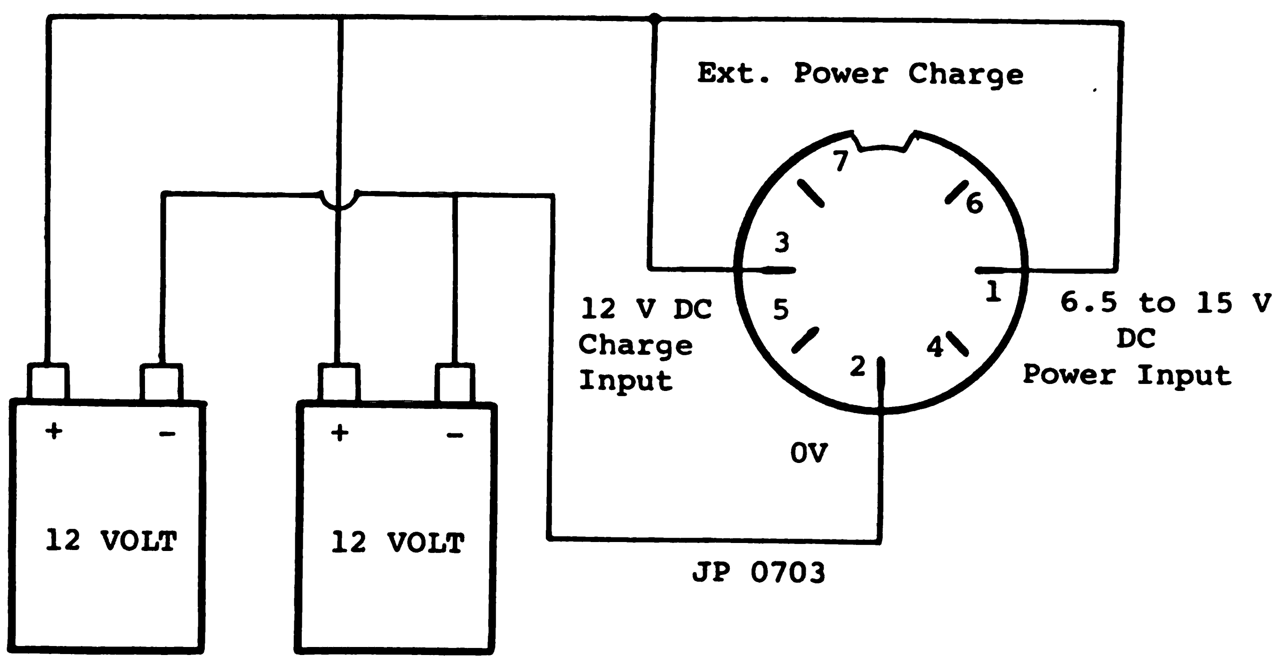


Figure 3-5. Vibration recorder power circuit.

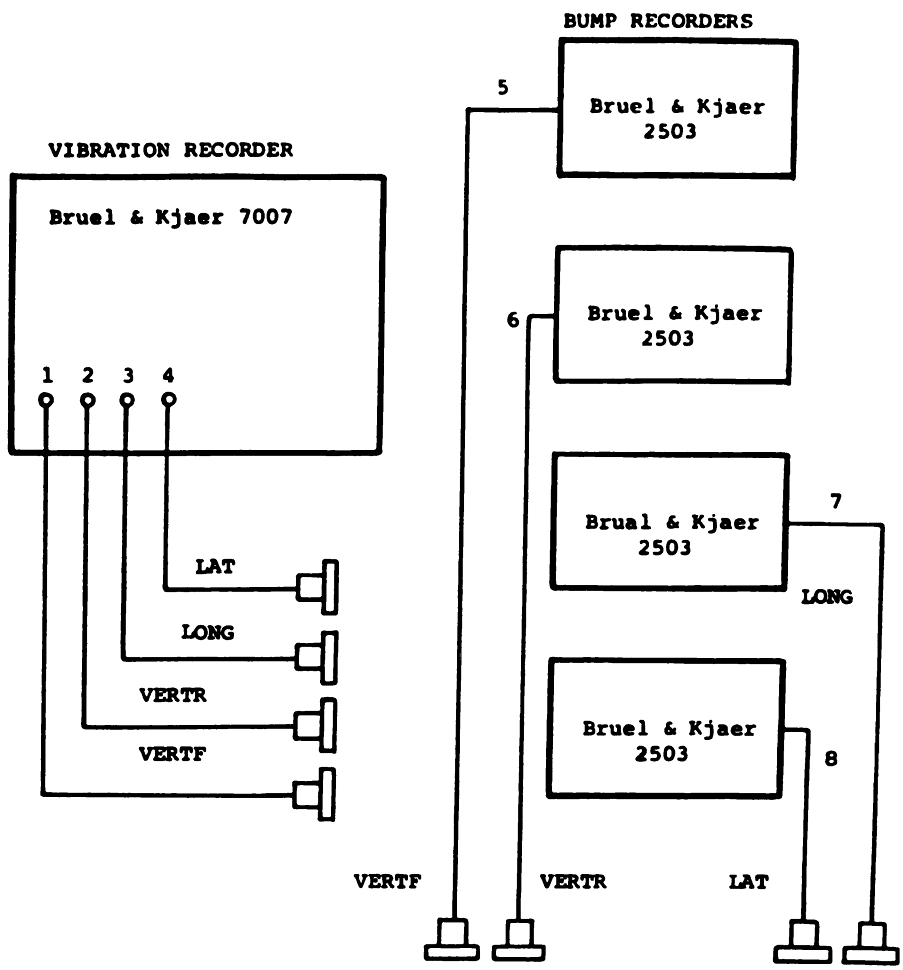


Figure 3-6. Instrumentation schematic.

Mounting the accelerometers was accomplished using 10-32 UNF metal studs. Mounting holes were tapped in the hardwood floor and the steel corner column of the trailer. With this hard mount, mechanical filtering was not deemed necessary.

3.3 TEST PLAN

The trailer/container was shipped through an intermodal distribution system. It was placed on a rail flatcar in Rochester, NY and line-hauled, with no stops for car changes, to Chicago, IL on Conrail tracks. In Chicago, the trailer was grounded and trucked to the North & Western Railroad. The container "box" was removed from the trailer chassis and placed on top of another similar container in a double-stacked "well" car. It was then line-hauled to Fremont, NE. The container was transferred to a well car on the Union Pacific Railroad and hauled to Los Angeles, CA. Upon arrival, it was grounded and trucked to a regional distribution facility in Whittier, CA. The recording devices were turned off, disconnected and returned to Rochester, NY. See Figures 3-7 and 3-8.

The various railways are identified on the map shown in Figure 3-9. Computerized summaries showing the train movements were received. Through these records, all train routings could be traced. By using this information, running times were determined and plotted on the chart in Figure 3-10.

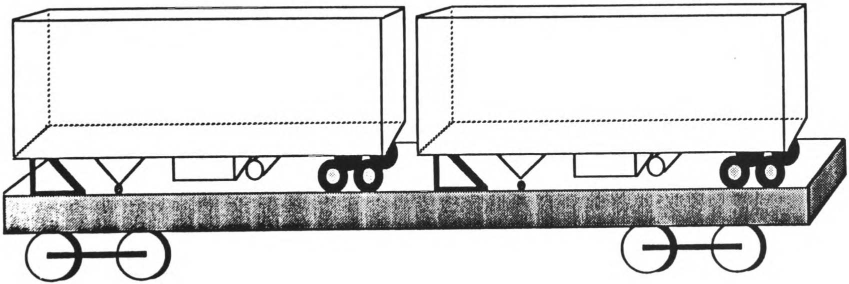


Figure 3-7. Trailer-on-flat car.

Figure 3-8. Container-in-well car.

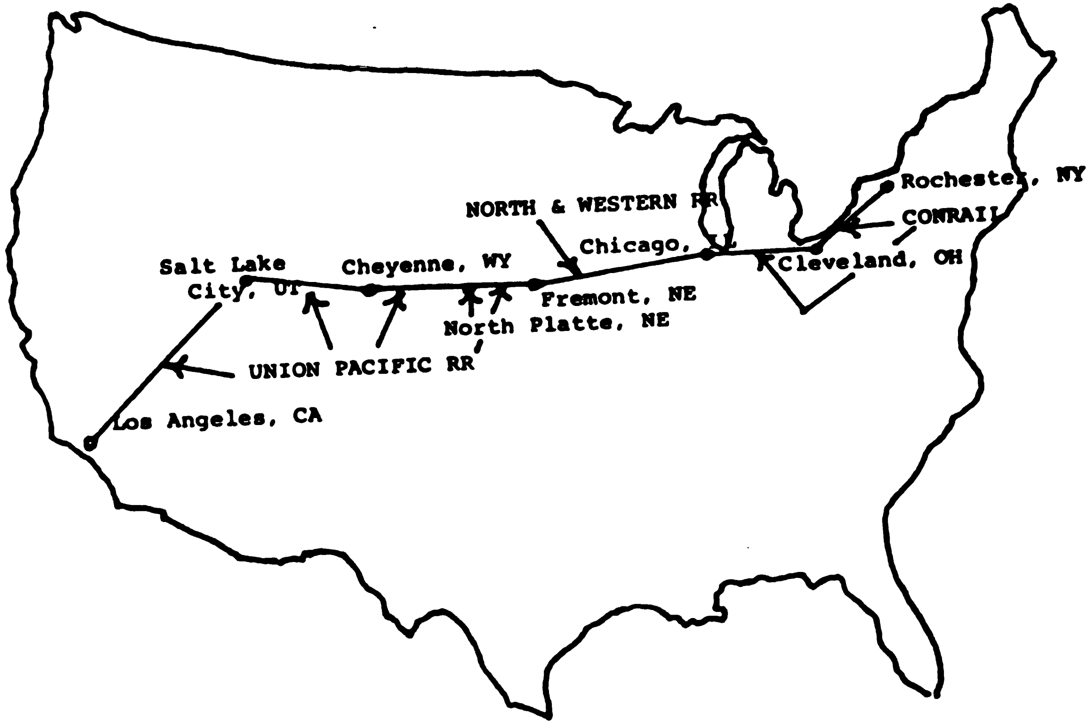


Figure 3-9. Rail route map.

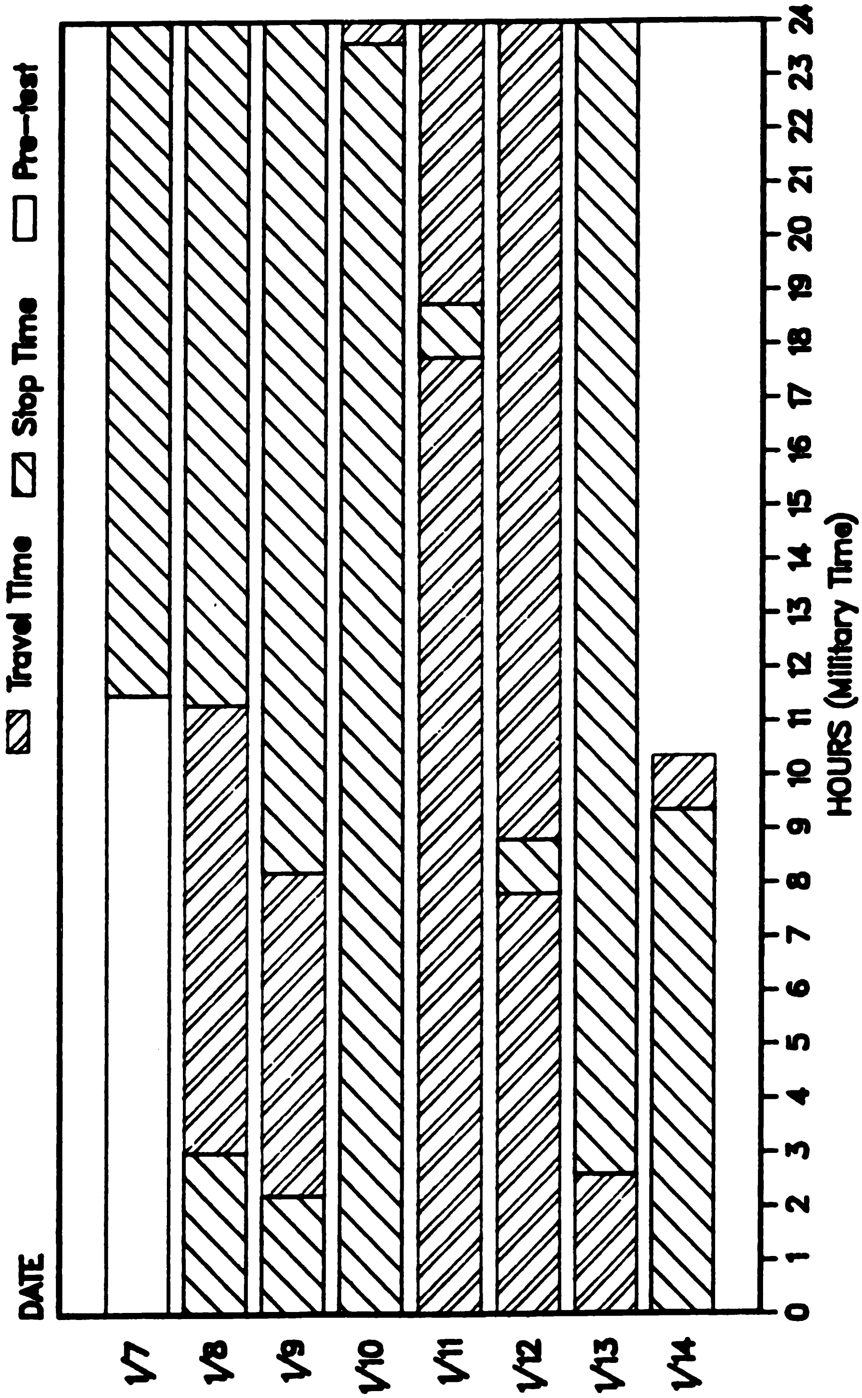


Figure 3-10. TOFC/CIWC travel times.

Running times were important considerations, because train vibrations were measured both at rest and underway. For purposes of the laboratory test format, only "live" data was desired. A method of isolating live data was based on the timed "on-sequence" for the recorder and the accompanying train status. See Table 3-1 for details.

Table 3-1. Train Status.

TOFC	DATE	TIME	STATUS
	1/7	11:30	Recorder activated
	1/8	02:59	Depart Rochester, NY (Conrail)
		11:17	Arrive Cleveland, OH
	1/9	02:10	Depart Cleveland, OH
		08:10	Arrive Chicago, IL
		08:30	Trailer grounded
	1/10	05:38	Trailer transferred (North & Western RR)

CIWC	DATE	TIME	STATUS
	1/10	07:00	Arrive North & Western RR
		23:37	Depart Chicago, IL
	1/11	13:05	Arrive Fremont, NE
		13:17	Depart Fremont, NE (Union Pacific RR)
		17:45	Arrive North Platte, NE
		18:45	Depart North Platte, NE
		21:10	Arrive Cheyenne, WY
		21:20	Depart Cheyenne, WY
	1/12	07:50	Arrive Salt Lake City, UT
		08:45	Depart Salt Lake City, UT
	1/13	02:35	Arrive Los Angeles, CA
		10:41	Well car on unloading ramp
		12:45	Container grounded
	1/14	09:21	Container picked up by Golden Eagle Express
		10:20	Container arrived at distribution center in Whittier, CA

All times shown are Eastern Standard time, and are based on a 24-hour clock. Dates listed are from 1/7/87 to 1/14/87.

CHAPTER FOUR

DATA ANALYSIS

4.1 RANDOM VIBRATION DATA

Vibration data was processed on a Zonic 6088 Spectrum Analyzer. The taped data was classified according to train movements so that only live segments would be used to define the laboratory test profile. Each of the live segments was processed separately and then compiled for a general profile. Processing was undertaken at a tape speed of 381 mm/sec. A total of 16 averages were taken for each nine meter segment. Comparisons are shown in Appendix D.

After determining the PSD profiles for each axis, the input frequencies were identified using a peak selection technique described in the Zonic 6088 Operations Manual. This allowed the noise to be subtracted from the data. Noise floor levels are shown in Figure 4-1. This process was done on an axis-by-axis basis, since the laboratory equipment could generate only single degree of freedom motion.

4.2 TRANSIENT SHOCK DATA

Shock data recorded on paper tape was transcribed and entered into an IBM PC XT computer. A LOTUS 1-2-3

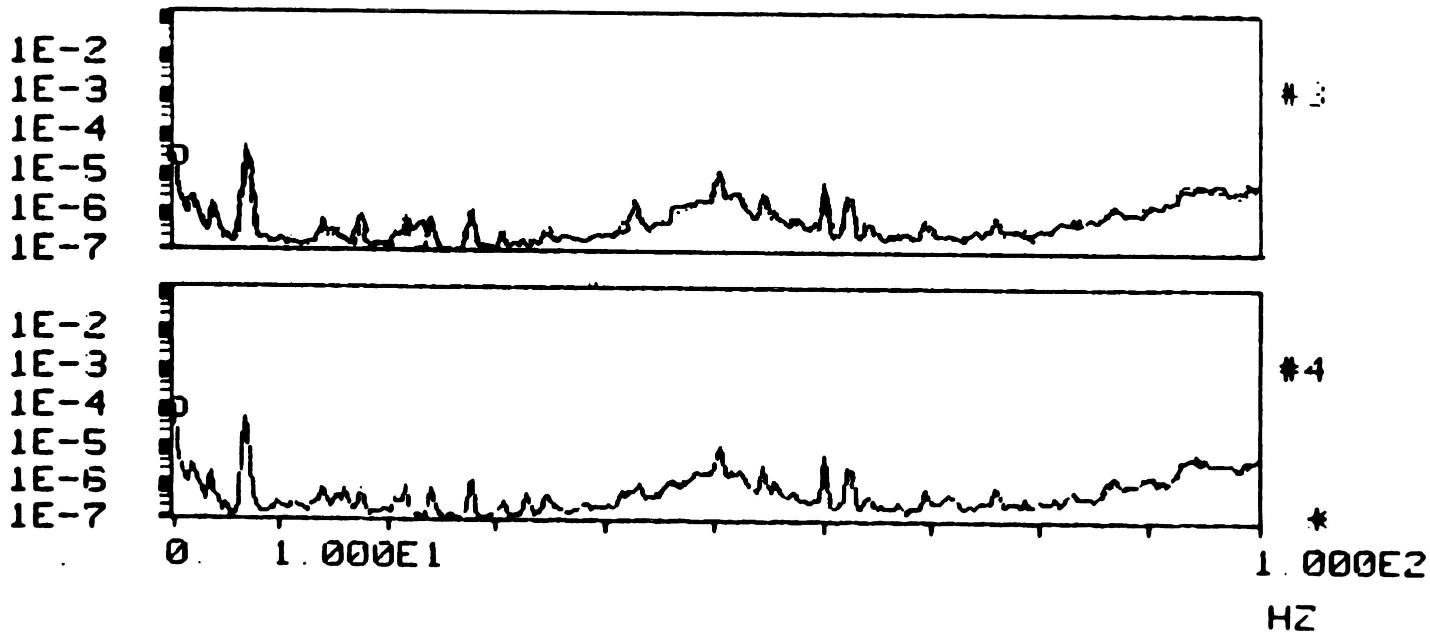


Figure 4-1. Sample data showing noise floor.

spreadsheet was used to manipulate the data and prepare the statistical reports. Full printouts are listed in Appendix E.

In the sample data entry shown in Figure 4-2, the shock events at each location are tabulated and listed as to the Day, Hour, and Minute of occurrence. The Velocity change is calculated and listed. These steps are all made possible through the macro-program which is used with the spreadsheet.

Values were double-checked for accuracy of velocity calculations. The presence of large values for accelerations were tested to see if they indicated recorder error.

4.3 VIBRATION RESULTS

Vibration data on the TOFC portion of the study revealed a broad-band maximum PD level of 1.5×10^{-4} g^2/Hz, on the lateral axis, from 5 to 10 Hz. This indicates suspension resonance. Kenworthy (1979) found a resonance at 1 Hz, with a PD value of 2.5×10^{-3} g^2/Hz, for TOFC. The current study also found a resonance at 2 Hz. Neither of the studies show significant energy at higher frequencies. See Figures 4-3 and 4-4.

Also of interest is a study on the Canadian Pacific Railroad reported by Naylor (1987). It was noted, in TOFC

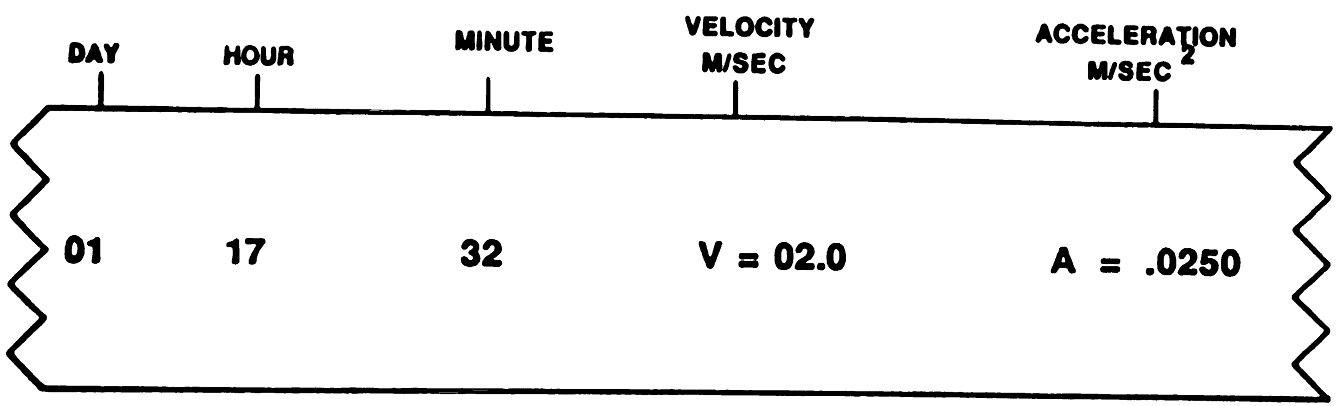


Figure 4-2. Bump recorder data tape.

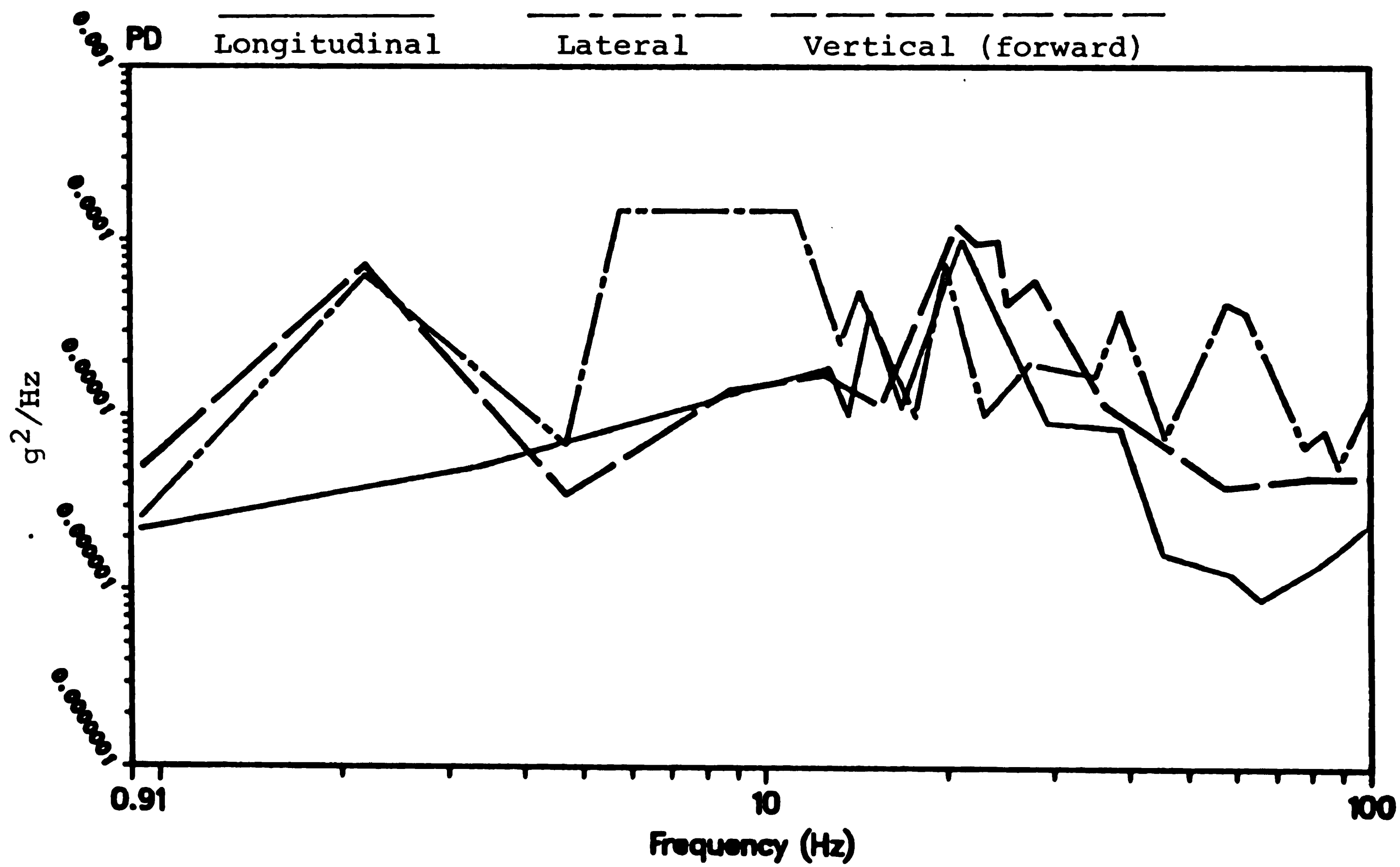


Figure 4-3. TOFC, Rochester to Chicago - vibration.

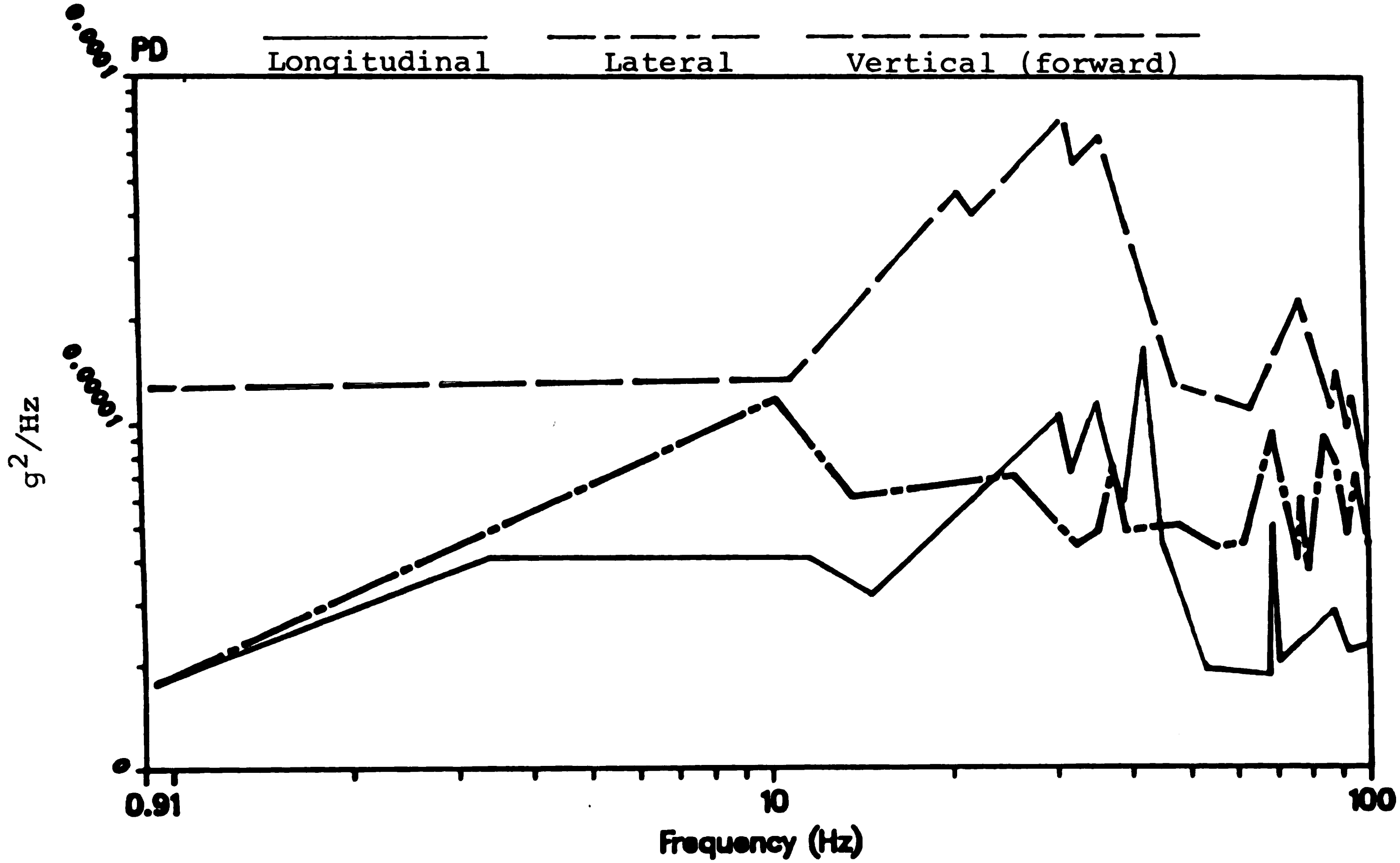


Figure 4-4. CIWC, Chicago to Los Angeles - vibration.

shipments, the vertical response over the king pin, on the trailer floor, demonstrates a larger vibration response if the trailer air brakes are set as it rests on the flatcar. In the current study, the trailer brakes were not set during the TOFC portion of the journey, and thus explains the lower vibration level.

It should be noted that the cable connecting the vertical vibration accelerometer over the rear wheels failed during the test. The only vertical vibration data presented was measured in the forward location.

The CIWC analysis indicates quite a different profile. Little energy is present at low frequencies of 0 to 8 Hz. The vertical axis shows readings of highest energy levels in the 10 to 13 Hz range, with the peak at 7×10^{-5} g^2/Hz. Removing the truck suspension system altered the low frequency response of the system. However, the well car suspension is observed to be the input frequency in this range. The overall difference between the random vibration characteristics of TOFC and CIWC modes is a flattening of vertical and lateral responses, below 10 Hz, for the latter. The longitudinal input remains the same.

4.4 SHOCK RESULTS

Shock data recorded for the two modes indicated a shifting pattern for input shock ranges. Each axis and monitoring position experienced a specific shock level distribution. For TOFC, the results were:

Vertical, front	2-5 g's	76%
Vertical, rear	4-6 g's	50%
Longitudinal	0-2 g's	75%
Lateral	11-12 g's	50%.

For CIWC, the results were:

Vertical, front	2-3 g's	83%
Vertical, rear	2-7 g's	75%
Longitudinal	1-4 g's	13%
	7-10 g's	20%
	15-20 g's	44%
Lateral	6-13 g's	79%.

The results summarized above are taken from Figures 4-5 to 4-15.

Since the distribution range for shock levels varied axis-by-axis, a representative test procedure must also vary these inputs. The test format explained in the next chapter will address this issue.

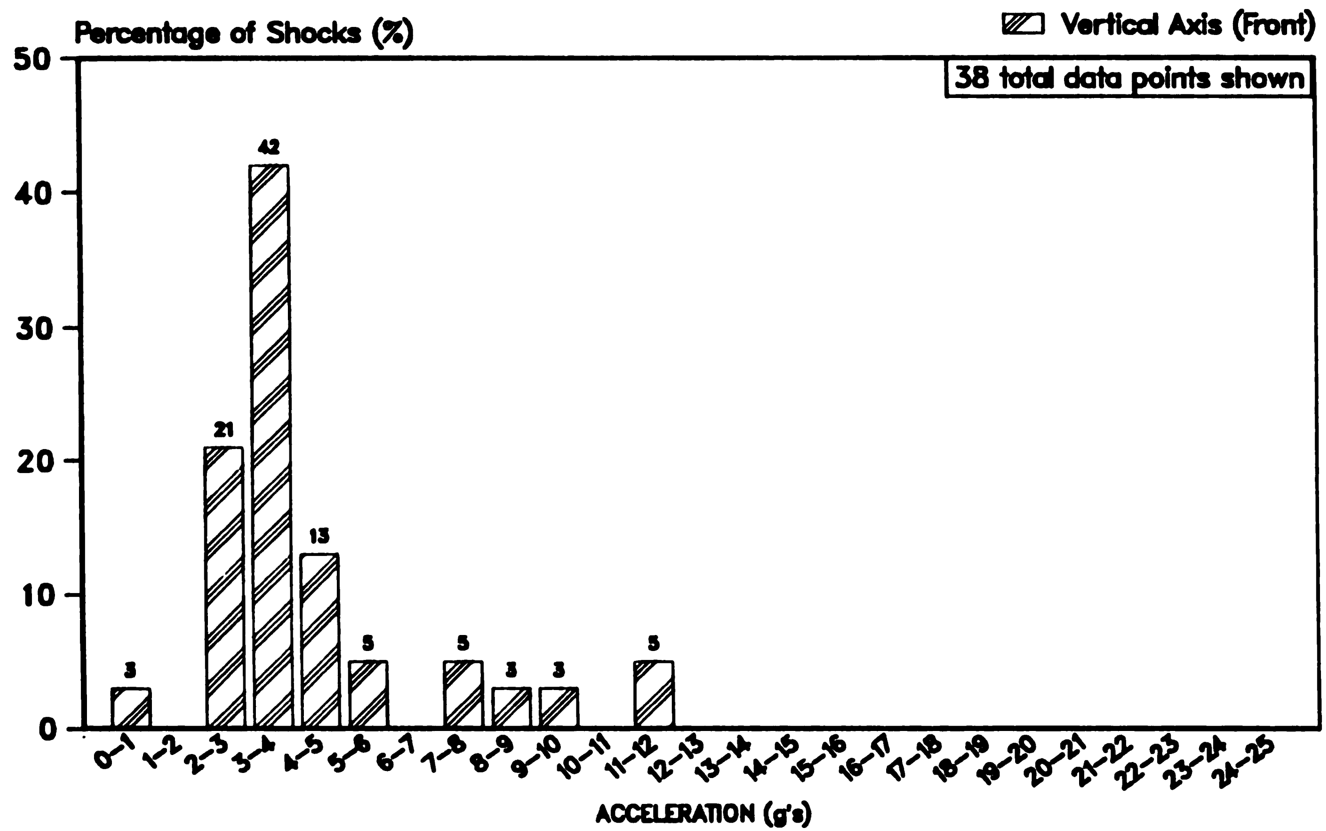


Figure 4-5. TOFC - shock distribution, vertical (front).

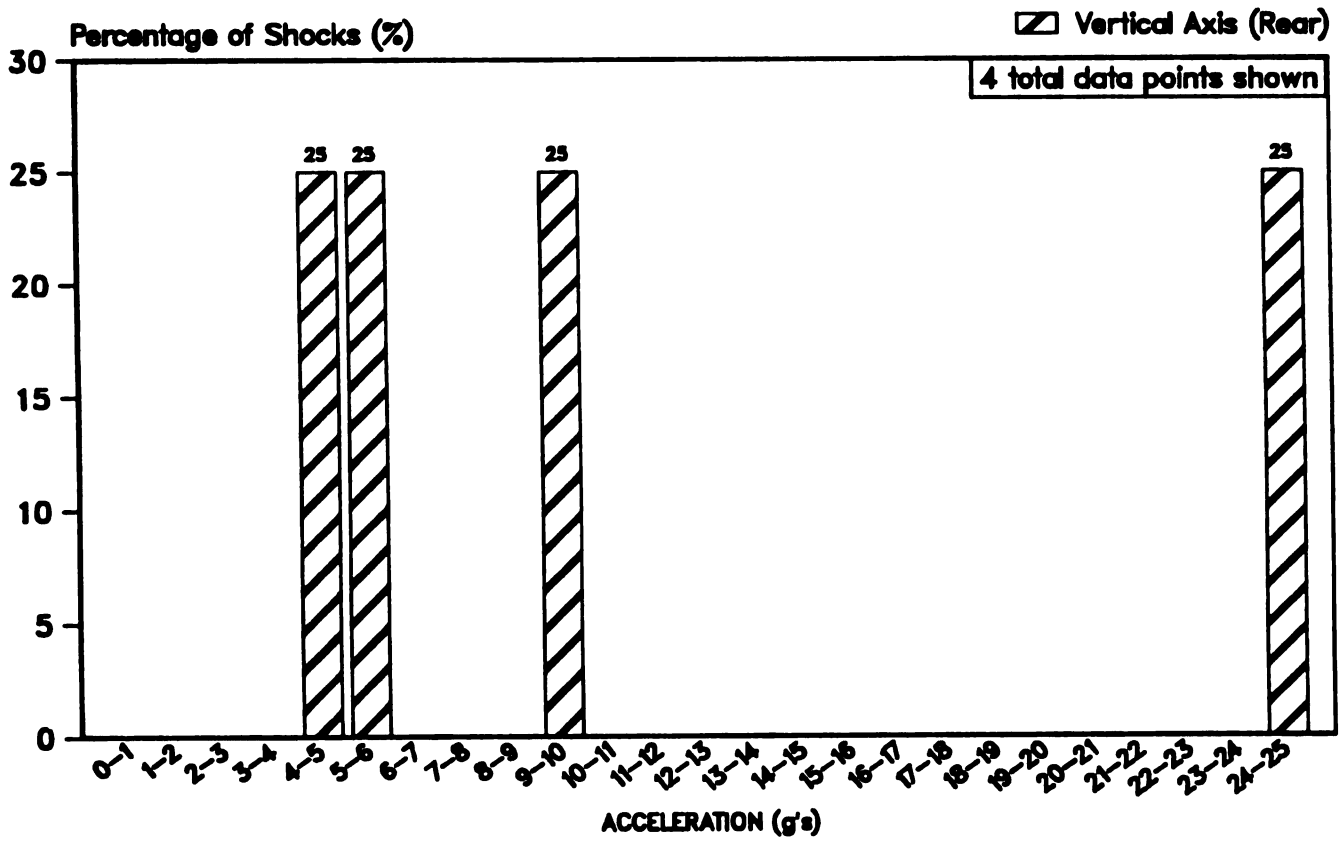


Figure 4-6. TOFC - shock distribution, vertical (rear).

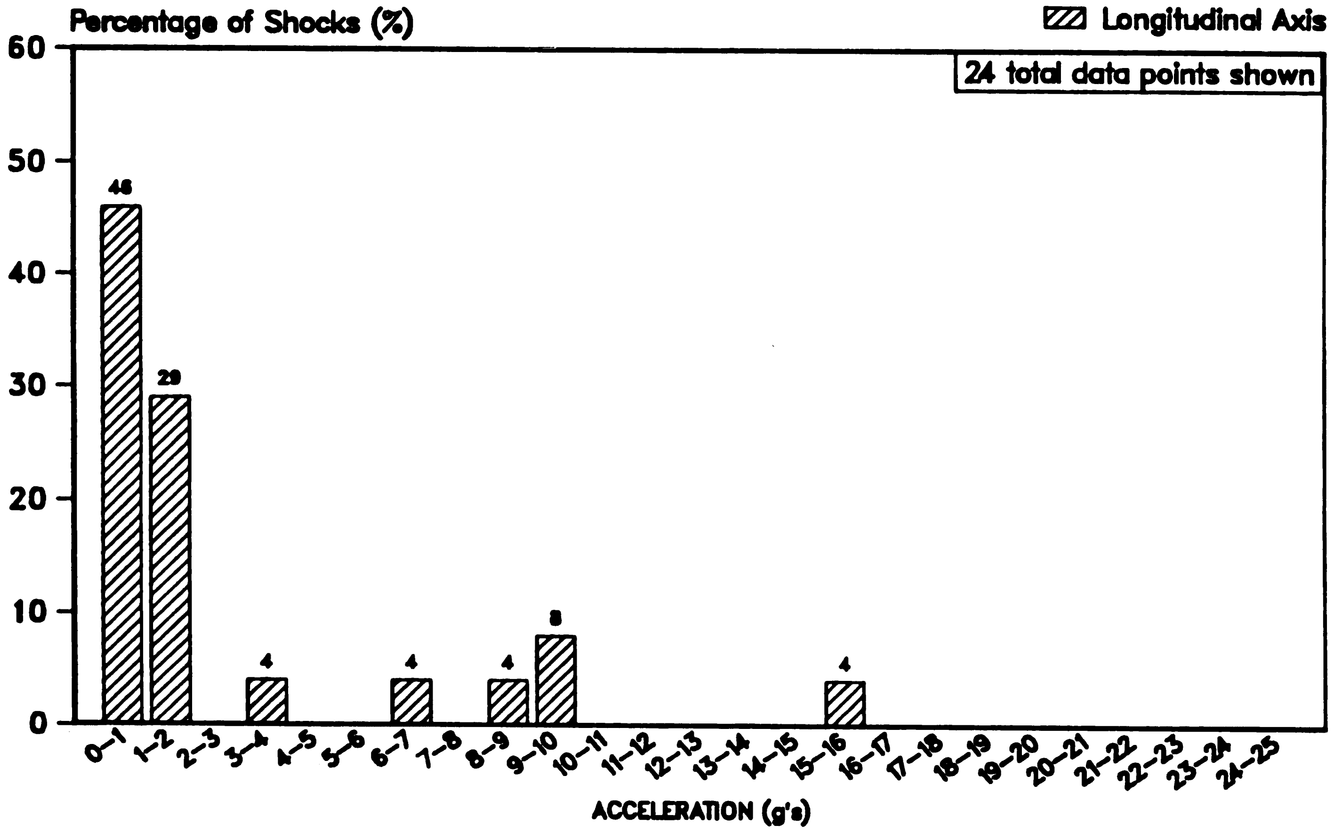


Figure 4-7. TOFC - shock distribution, longitudinal.

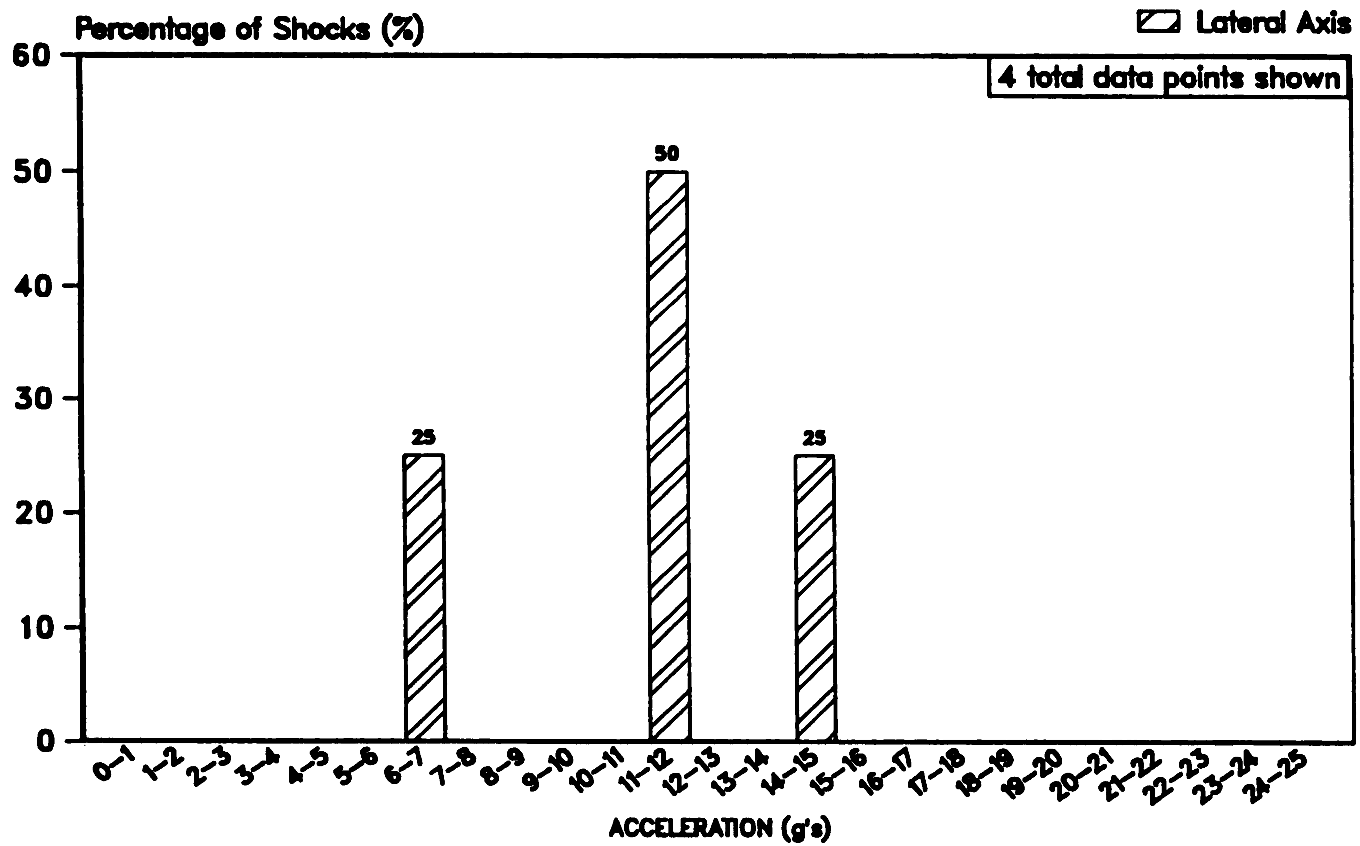


Figure 4-8. TOFC - shock distribution, lateral.

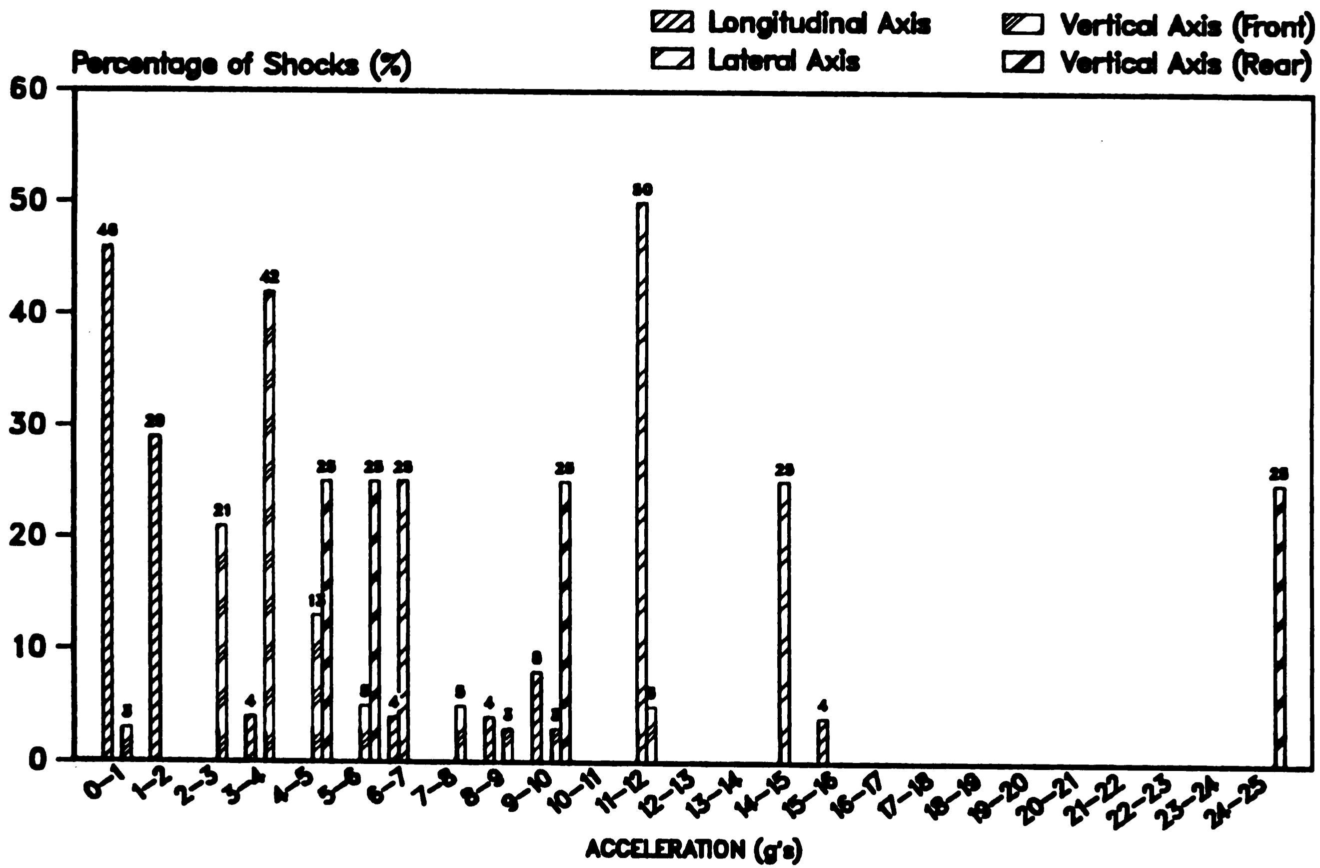


Figure 4-9. TOFC - shock distribution, composite.

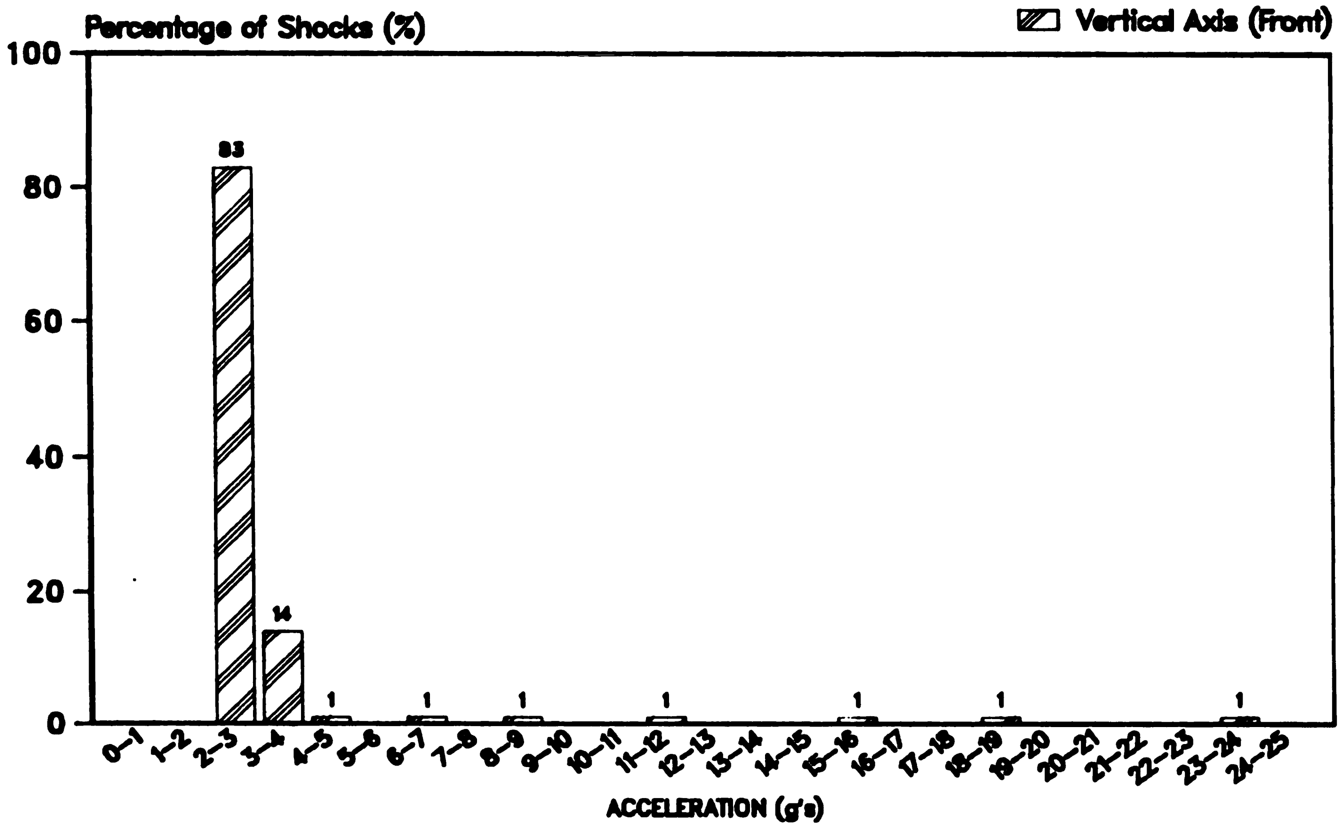


Figure 4-10. CIWC - shock distribution, vertical (front).

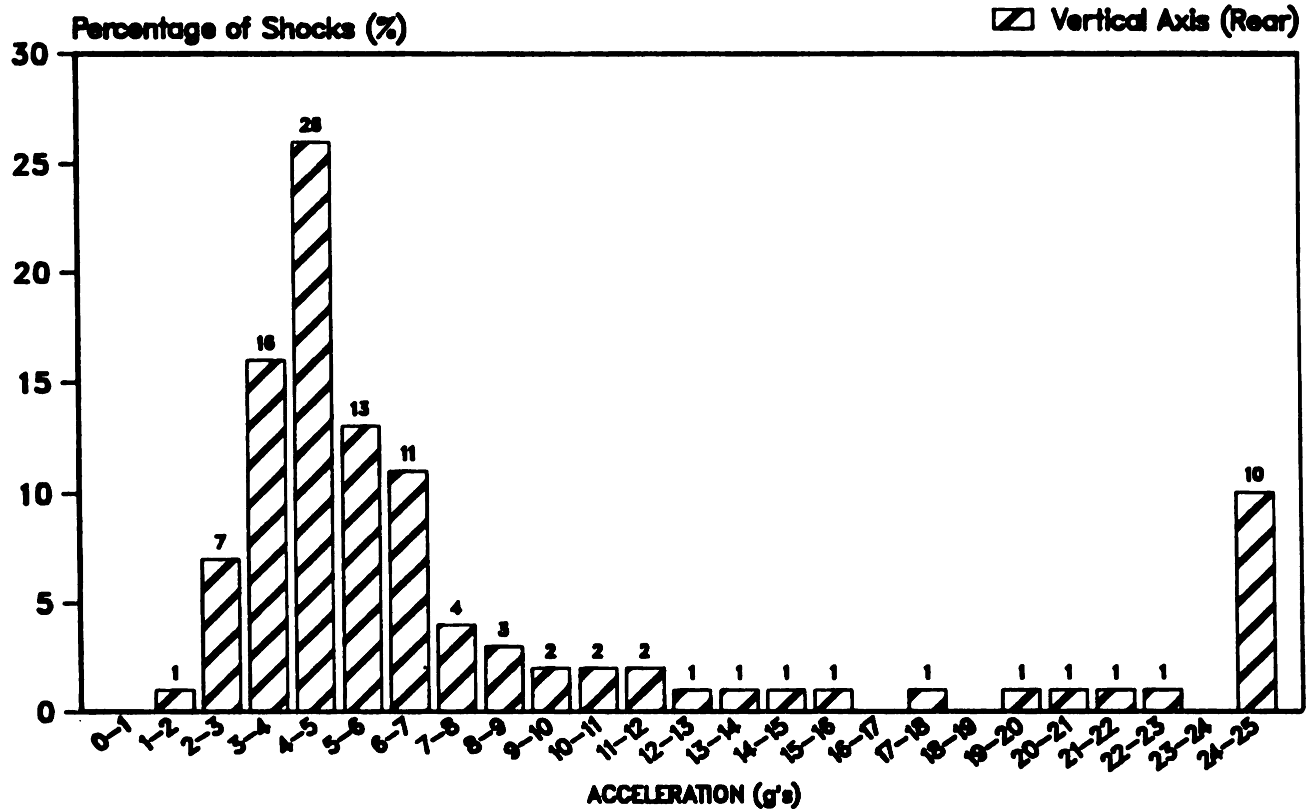


Figure 4-11. CIWC - shock distribution, vertical (rear).

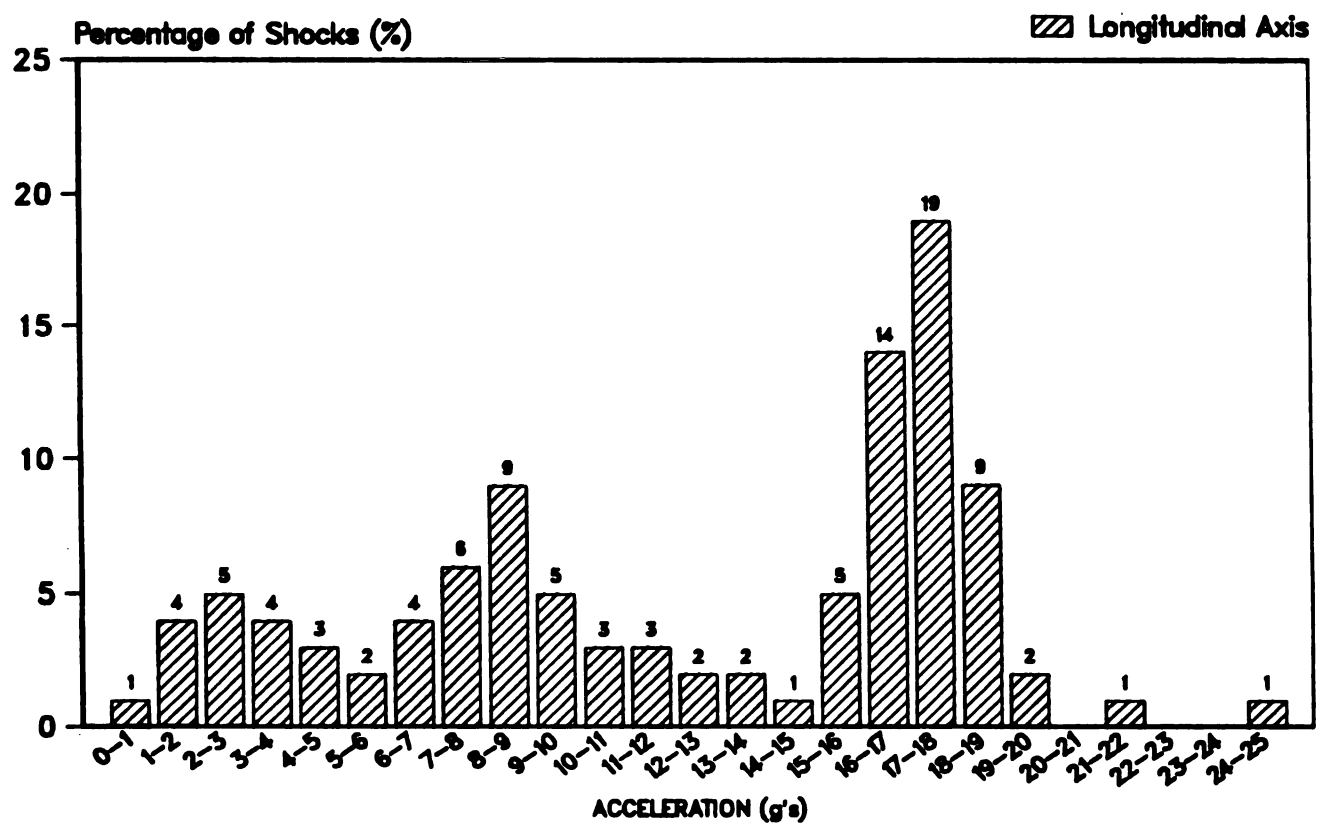


Figure 4-12. CIWC - shock distribution, longitudinal.

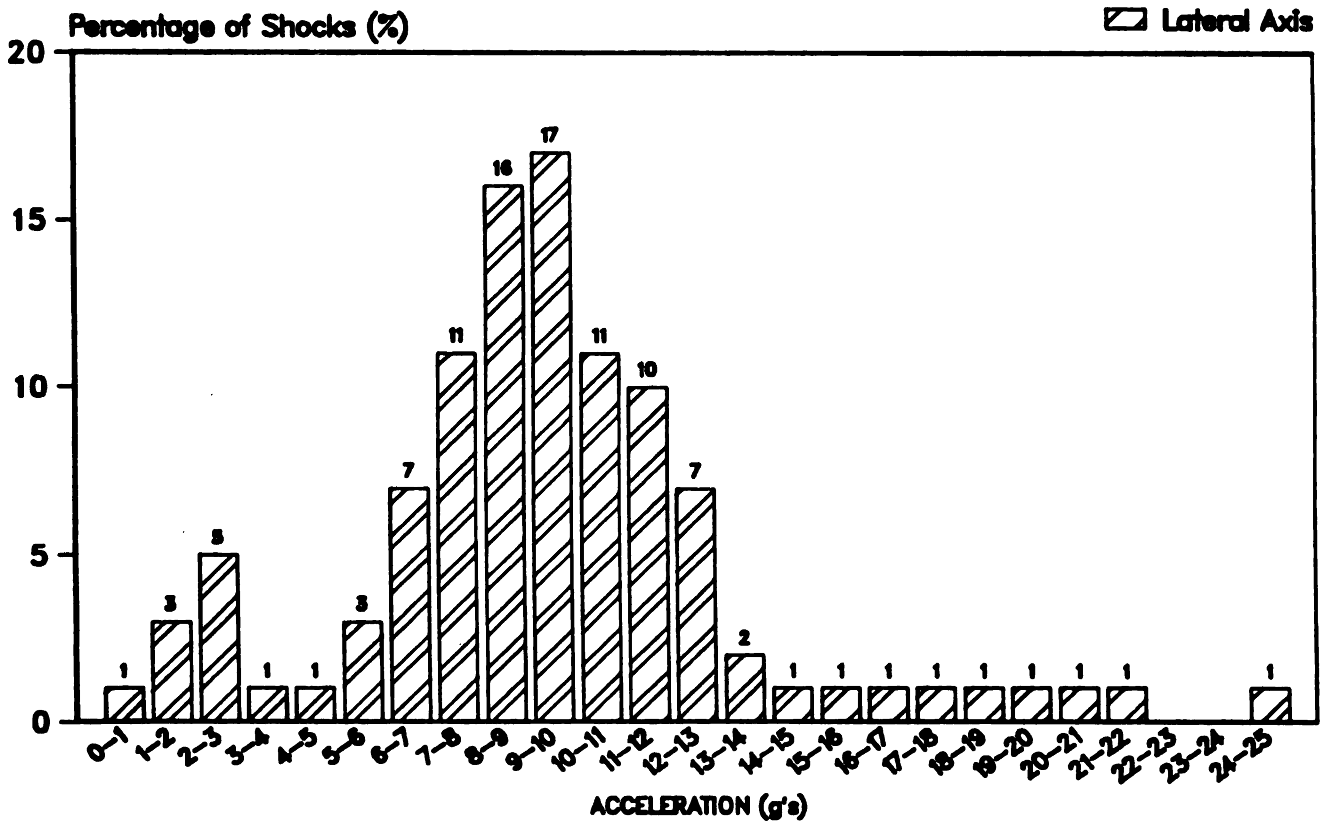


Figure 4-13. CIWC - shock distribution, lateral.

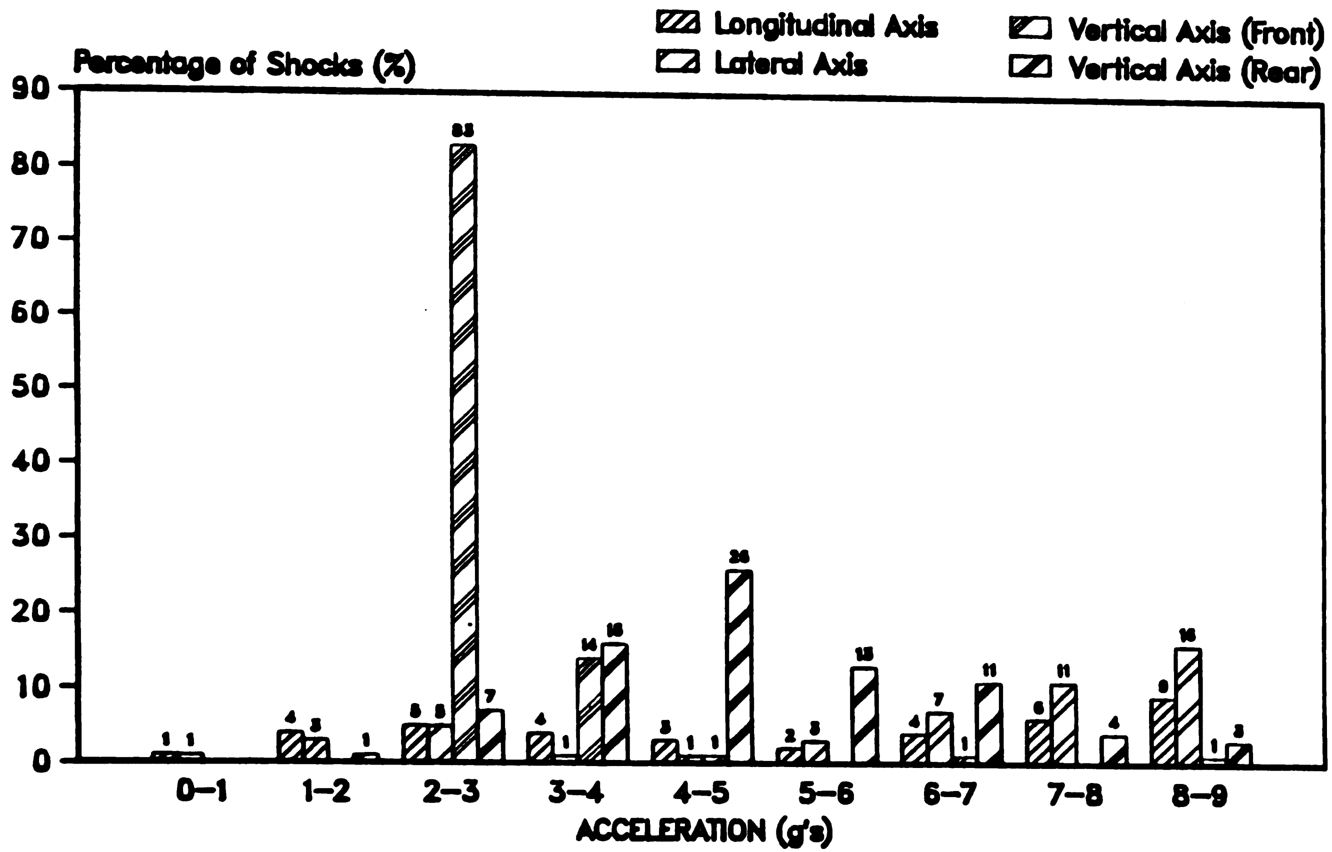


Figure 4-14. CIWC - shock distribution, composite 0-9 g.

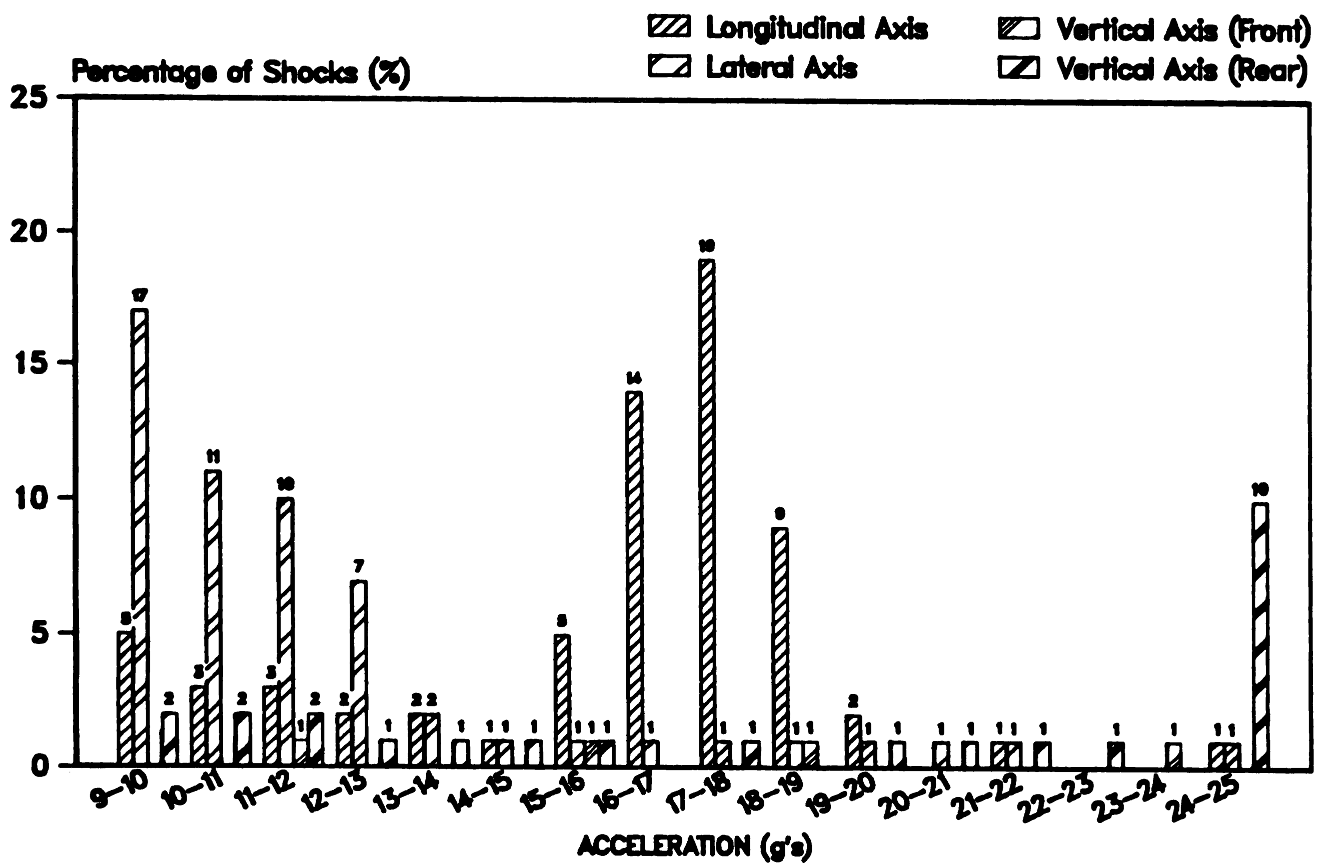


Figure 4-15. CIWC - shock distribution, composite 9-25 g.

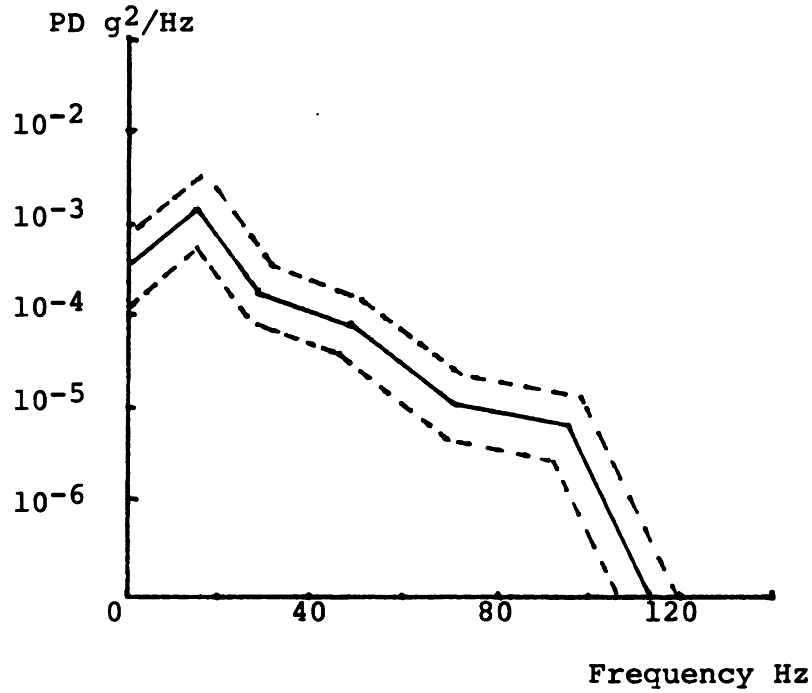
CHAPTER FIVE

LABORATORY TEST PROFILE

The two PSD plots shown in Chapter Four are the summary profiles for TOFC and CIWC modes, and the basis for the laboratory test. One of the main objectives in this test was to generate a simulation which incorporated <u>both</u> the random vibration and the transient shocks. This goal was achieved through the use of a digital control system and an electrohydraulic vibration table.

Instrumentation for the digital control system included a Scientific Atlanta Spectral Dynamics SD 420 spectrum analyzer. The coordinates for the profiles were programmed onto the operations disk with the computer. A real-time display identified the input signal and the tolerance band established, as in Figure 5-1. The hydraulic system was operated through an MTS Servo Controller 406. This unit allowed the vibration table to be driven directly from tape as a closed loop, sine wave input, a random signal or a transient shock generator. Figure 5-2 shows the equipment used.

In order to generate a shock-on-random simulation, the two signals were combined on the operations disk. A random



Broken line defines the tolerance band used in a random test.

Figure 5-1. Random vibration input.

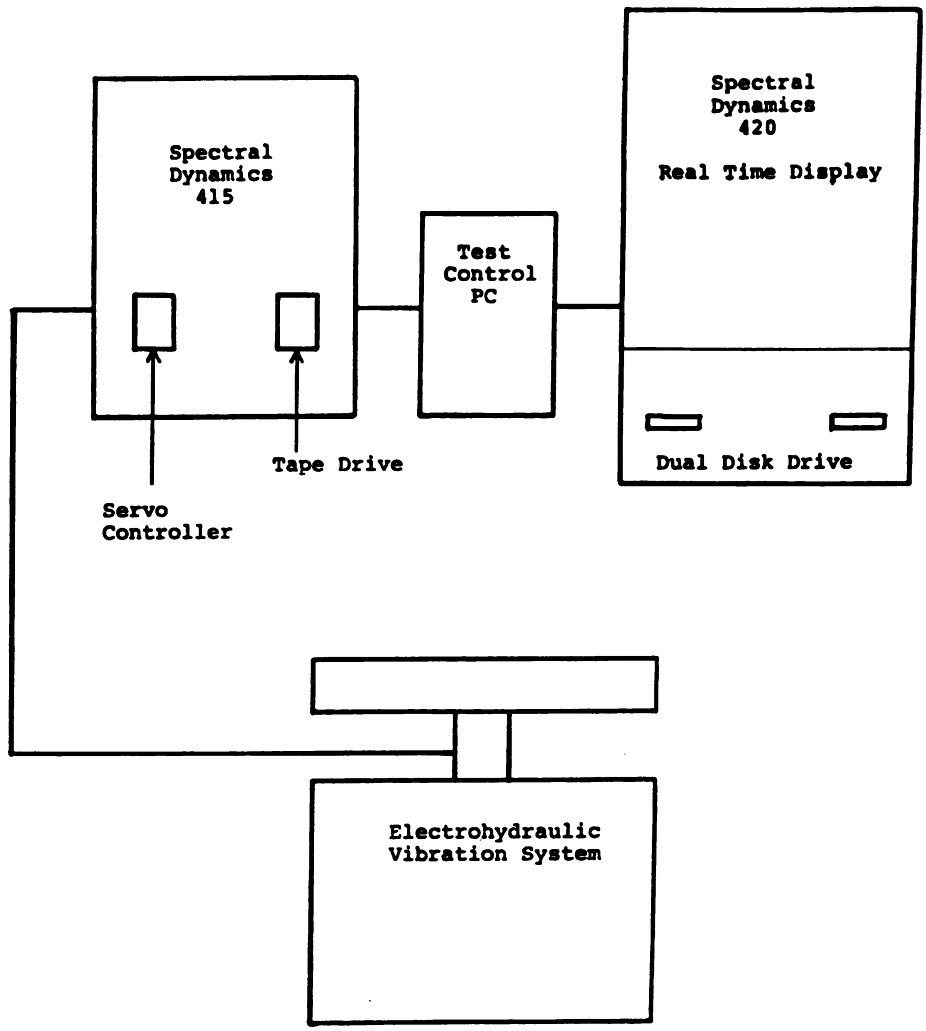


Figure 5-2. Electrohydraulic vibration system.

vibration profile is shown in Figure 5-3. This represents a portion of the measured data. By utilizing the peak selection technique mentioned in Chapter Three, the X-Y coordinates for one channel were determined and are listed in Table 5-1. X-coordinates refer to frequency levels measured in Hertz, and Y-coordinates identify the corresponding Power Density levels, in units of g^2/Hz. The X-Y coordinates for the random signal were programmed on an operations disk. Individual transients were then programmed on top of the profile. In the current test, a 15 g, 11 ms half-sine shock pulse was programmed to occur every 10 seconds for a period of 15 minutes. See Figure 5-4. It is possible to program each shock as it occurred in the measured environment. However, the test level is set to generate the <u>maximum</u> <u>normal</u> dynamic inputs to the product. The flexibility afforded by a digital control system allows each test to be varied, if desired.

The vibration system used for this test utilized a 500-pound table. The levels of energy shown in the TOFC and CIWC profiles were too low to drive the table. For preliminary evaluation, the test level was amplified four orders of magnitude, so that the table would respond as desired. A feedback accelerometer was used to monitor the table. The inputs to product/package systems were generated on an axis-by-axis format, as the table had only single degree of freedom capabilities.

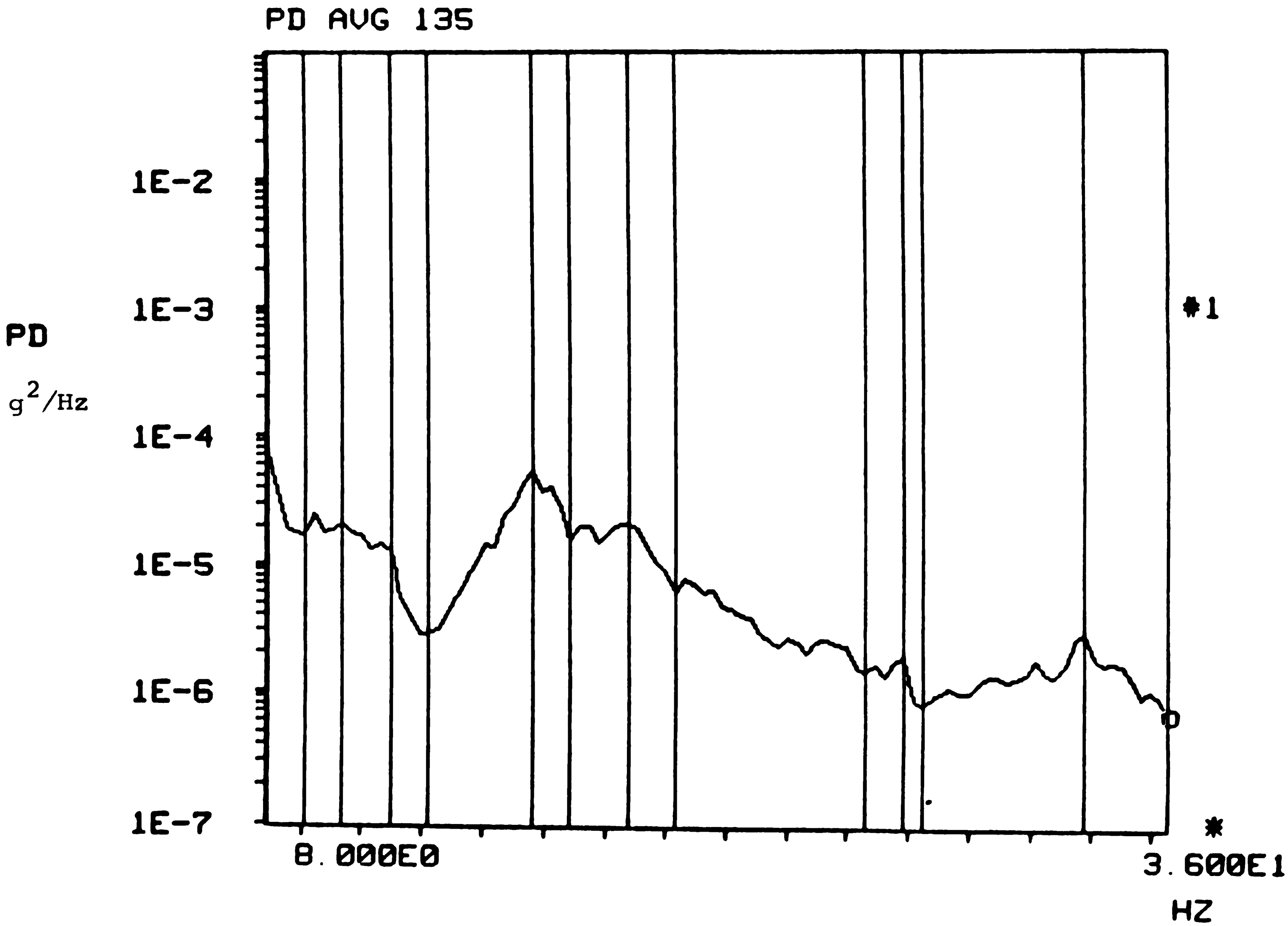


Figure 5-3. Peak selection.

Table 5-1. Peak Coordinates.

INDEX	X HERTZ	Y #1
2.200E+1	6.875E+0	7.167E-5
2.600E+1	8.125E+0	1.691E-5
3.000E+1	9.375E+0	1.970E-5
3.500E+1	1.094E+1	1.220E-5
3.900E+1	1.219E+1	2.693E-6
5.000E+1	1.562E+1	5.205E-5
5.400E+1	1.687E+1	1.528E-5
6.000E+1	1.875E+1	2.023E-5
6.500E+1	2.031E+1	5.862E-6
8.500E+1	2.656E+1	1.426E-6
8.900E+1	2.781E+1	1.746E-6
9.100E+1	2.844E+1	7.627E-7
1.080E+2	3.375E+1	2.813E-6
1.170E+2	3.656E+1	7.067E-7

X-axis is measured in hertz

Y-axis is measured in g^2/Hz

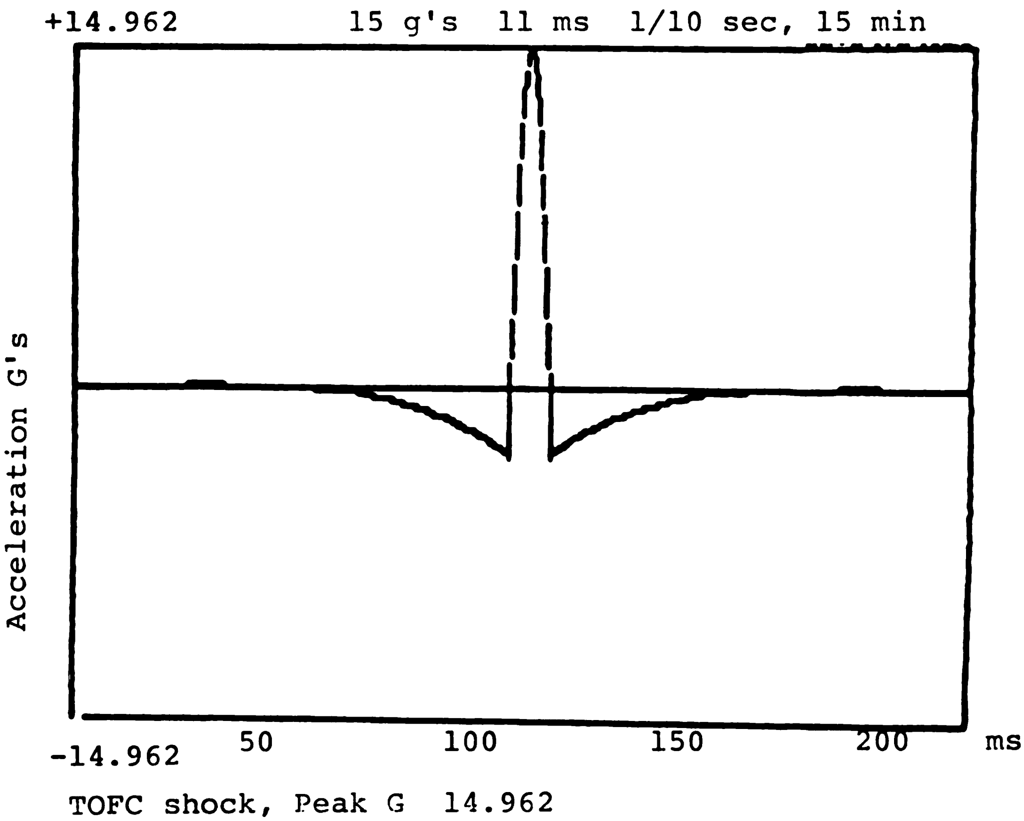


Figure 5-4. TOFC half-sine shock.

CHAPTER SIX

OBSERVATIONS

The following observations were made during the process of literature review, data collection and analysis. They are intended to provide additional insight to those readers conducting environmental measurments or seeking information on the characteristics of the dynamics found in transportation networks.

1. Test methodology development and data measurement took place between March, 1986 and February, 1987. During that period five rail trials were undertaken between Rochester, NY and Los Angeles, CA. These included: one shipment of over-the-road truck from Rochester to Chicago, IL combined with TOFC from Chicago to Los Angeles; one CIWC run from Los Angeles to Rochester; and three runs from Rochester to Los Angeles in the TOFC - CIWC format described in this study. Data presented in this study are from the second such trial.

2. Multiple channel data collection requires many cables, lead wires and accelerometers. A wiring harness was used to eliminate tangles and to reduce set-up time. It also

reduced the amount of abuse received by the cables. Prior to using the harness, two cable shields were broken and one center hot wire failed. It is also suggested that micro-dot connecting links be kept on the ends of disconnected cables at all times.

3. Unattended instrumentation is often powered by rechargable nickel-cadmium batteries. Useful charge-life is uncertain with these systems. Power failures occurred on <u>some</u> of the instruments during the first three trials. Nickel-cadmium batteries tend to develop a short "charge memory" if they are recharged frequently after only partial discharge. The solution to this problem involved the use of 12-volt gelatin batteries. They can be shipped in any position without the spillage of lead-acid batteries. Additional parallel units can be added for longer trips, or to include periods of storage.

4. In situations where test instruments travel one-way to collect data, personnel must be trained to remove them and prepare them properly for return. A training session with warehouse personnel in Los Angeles was effective in minimizing improper handling of instruments. Also, after the first three runs, permanent containers were developed using large plastic shells with hinged lids, made by the Hardigg Co., to encase the instruments, wiring harnesses, batteries, accelerometers and a few small tools.

Polyethylene foam was fabricated as interior cushioning material.

5. Accelerometer mounting was accomplished with 10-32 UNF metal studs. No problems were encountered with tapped holes in either the hardwood trailer floor or the steel support columns. One temperature-controlled shipment required a refrigerated trailer. Such trailers have grooved floors which allow accelerometers to be epoxied in the recesses, out of reach of the forklift and pallets. During this trial shipment an angle iron bracket mounted to protect a forward accelerometer was sheared off due to load shifting. That accelerometer failed. The one mounted in the groove was undamaged.

6. It is standard practice to use spectrum analyzers to process random vibration data. A sensitivity or range setting of 100 mv/m/sec was a fair compromise between a less sensitive range that minimizes cross-talk, and one more sensitive which amplifies the noise levels making it more difficult to select peak resonances.

7. Cargo placed in a trailer/container, over the rear wheels or on the rear overhang, will experience the most severe shock <u>and</u> vibration inputs.

8. Sources of transient loadings for rail cars, in the vertical axis, would include road crossings, switch

junctions and rail joints. These contain both short duration, 30 ms, and longer duration, 100 ms, pulses.

9. The number of shocks over 2 g's was fairly large, over 700 in each axis, for the 6-day trip. Also, longitudinal shocks had higher g-levels than expected with the articulated couplings of CIWC shipments. Review of the raw data revealed that over 90% of those shocks were less than 30 ms duration. Therefore, they generated little energy. The only long duration shocks, those over 100 ms, occurred during the loading and unloading operations.

10. Coupling shocks occur as train cars are joined in classification railyards. An average impact speed for coupling operations would be 8 miles per hour. Shocks of 10 g's, 30 ms duration are typical of those generated with standard draft gear couplers. Cushion underframe draft gears have a travel range of 24 inches during coupling, and experience shocks of 2.3 g's and 250 ms duration. TOFC and CIWC shipments are not supposed to be coupled with the trailer/container units in place.

11. Shocks in empty or lightly loaded vehicles were found to be much higher than heavily loaded ones. The majority of the shocks increased from 5 to 15 g's. Ninety percent of the durations were from 3 to 5 ms.

12. By far the most common vibration frequencies found in all forms of commercial carriers are between 1 and 12 Hz. These inputs are attributed to vehicle suspension systems. This characteristic is the same for both over-the-road truck suspensions and rail truck assemblies. The CIWC environment generates peak amplitudes at the high end of this range, near 12 Hz.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

1. The collection and analysis of data in this 2,877-mile rail distribution network marks the first published study of a commercial, non-experimental, CIWC shipment of more than 500 miles. Studies of such length are also scarce for TOFC modes. Soroka (1986), of the Ontario Research Foundation, indicated that a 1985 study of a TOFC shipment from Toronto, Ontario to Vancouver, British Columbia, on the Canadian Pacific Railroad, was never formally analyzed and published. In addition, Grosso (1987), of the Association of American Railroads, reports that a 5,000-mile boxcar vibration test in 1974 was never completely analyzed. Therefore, it has been determined that environmental data on long distance rail shipments in general, is limited.

2. The use of unattended instrumentation, described in the methodology chapter, was successful in recording the shock and vibration dynamics in all three axes. This technique has been established as the standard procedure for measuring all distribution networks utilized by the company sponsoring this study. Collected data is now used to

establish test parameters for each respective test simulation.

3. Evidence indicates the TOFC and CIWC rail transport modes are increasing in use. They offer a more cost-effective means to transport products for longer distances, especially distances greater than 1,000 miles. CIWC offers a significant economy of scale in freight volume transported versus fuel consumption.

4. Mainline rail systems have been improved through the replacement of jointed track with continuous welded track. Measured inputs to rail vehicles indicated the sharp vibration peaks have been eliminated as a result of this change. Input responses to rail vehicles traveling on continuous welded track were found to be more like wide-band random vibration. CIWC PSD profiles demonstrated such behavior between 0.91 and 10 Hz.

5. The current study found CIWC random vibration input to be one order of magnitude lower than TOFC. Maximum PSD values were found to be 1.5×10^{-4} g^2/Hz in the 5 to 10 Hz range for TOFC in the lateral axis. CIWC maximum was reached in the vertical axis and had a PD value of 7×10^{-5} g^2 /Hz. Most studies completed previous to the current investigation focussed on the low-end frequency scale. Low fequencies of 1 to 13 Hz are usually associated with vehicle suspension systems.

6. Shock data indicates that each axis is different, with respect to the g-level of the shocks occurring in that axis. The vertical front location experienced 76% of the inputs in the 2 to 5 g range for TOFC measurements, and 83% of the shocks in the 2 to 3 g range for CIWC. The vertical rear location encountered shocks in the 4 to 6 g range 50% of the time for TOFC and 2 to 7 g's 75% of the time for CIWC. Fifty percent of the lateral shocks for TOFC occurred between 11 and 12 g's. Seventy-nine percent of those for CIWC were between 6 and 13 g's. Longitudinal inputs for TOFC were relatively low, with 75% falling between 0 and 2 g's. Longitudinal inputs for CIWC were quite different. Only 13% fell at the low 1 to 4 g range. 20% occurred between 7 and 10 g's, while 44% were between 15 and 20 g's. The articulated coupling did not appear to reduce longitudinal inputs.

7. The vibration PSD profiles in this study were the basis for a laboratory simulation procedure. In addition to the vibration input, the transient shocks were considered. A preliminary test profile has been established which incorporates a 15 g, 11 ms half-sine shock pulse along with the random vibration signal. Observation of the test profile's effects on stretch-wrapped pallet loads of product indicate definite displacement of tiers when the transients are added.

8. Several aspects of this study have influenced management decisions. Cargo in the first trial run experienced significant load shift during the TOFC portion of the trip. Documented slides and video tapes of the difficult unloading process in Los Angeles altered existing shipping policy. In addition to stretch wrapping pallet loads, air bags were added to stabilize the lading. This solved the problem without the need to implement blocking and bracing techniques.

9. Another consideration involved product from Japan, which was shipped to Rochester via the Panama Canal. These products were hand-loaded overseas and used no pallets or slip-sheets. Management requested information about the CIWC environment to see if it was suitable for such cargo. Data from the second trial, Los Angeles to Rochester by CIWC, proved this method to be acceptable. This resulted in time and cost savings.

10. Preliminary test results, with containers of liquid chemicals, have shown the new procedure to simulate field damage more effectively. This has been attributed directly to the addition of transient shocks to the dynamic input. As a result, policy has been implemented to incorporate the test procedure as a means of package system evaluation for all product shipped TOFC and CIWC.

11. A new servo control system has been ordered to allow the electrohydraulic shaker to operate at levels actually measured in the field. The system currently requires the signal to be amplified in order to drive the table. A study is also underway to examine the possibility of installing a new vibration system with multiple degree of freedom capabilities. Such a device will require a larger foundation than the existing shaker. It is estimated a system of this type will cost approximately $750,000, installed.

CHAPTER EIGHT

RECOMMENDATIONS FOR FURTHER STUDY

More long distance studies should be undertaken in order to build the data base for probabilistic determination of peak vibration accelerations expected in the intermodal rail environment. It is also important that shocks be monitored as well, since they can have a significant effect on the resulting dynamic input to rail vehicles.

In addition to the above, it is important that the dynamics be measured in all axes. Nordstrom, et. al. (1986) of Packforsk in Sweden, have developed a Computer Aided Transport Simulation (CATS) test procedure. They stress the importance of testing with multiple degrees of freedom. Therefore all axes are monitored in field data collection procedures. The electrohydraulic shaker used in this simulation currently moves in vertical, horizontal and rotational directions. The test described above, can be amplified to reduce test time, if fatigue and abrasion are not major considerations. This would be determined on a case-by-case basis.

Current work utilizes software to sort vibration spectra and transient shocks in a biaxial format. Both vertical and horizontal field signals are processed and used. A program has been developed to merge these files and create the combined test. Initial trials with aeseptic food packages show the technique capable of simulating field damage more precisely than conventional sine-sweep procedures, or random-only inputs.

New test instruments are being introduced for measuring the combined dynamics of the environment and processing them directly through the computer. Through use of such devices, it will be possible to have tailor-made test programs for each specific distribution system.

APPENDIX A

FRAGILITY

APPENDIX A

FRAGILITY

Fragility is the term used to identify the acceleration necessary to damage the critical component in a product. The procedure, developed by Newton (1976), measures the combined effects of acceleration and velocity change on the product structure. Velocity change for a half-sine shock pulse is described by the equation:

$$\Delta V = A_p \, g \, \tau \, 2/\pi \qquad \text{(A.1)}$$

ΔV = Velocity change (in/sec)
A_p = Peak acceleration (g's)
g = Gravitational constant (386.4 in/sec^2)
τ = Duration (sec)
$2/\pi$ = Shape factor.

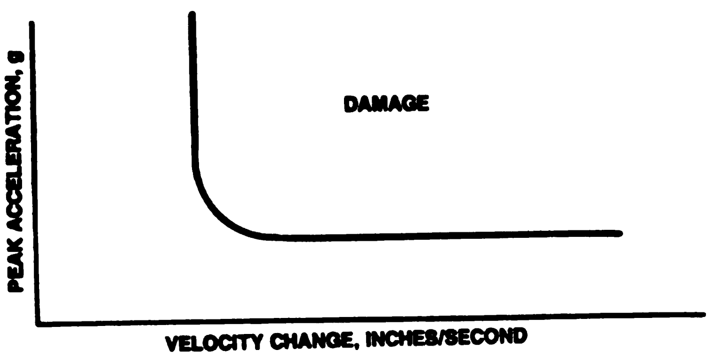


Figure A-1. Fragility curve.

See also, Brandenburg and Lee (1985).

The relationship between the shock pulse and the cushioned product response is shown in Figure A-2.

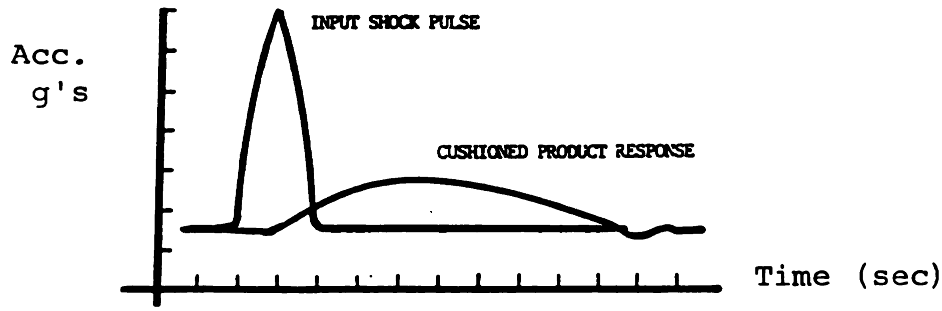


Figure A-2. Input shock and cushioned response.

The product and its critical component can be represented as shown in Figure A-3.

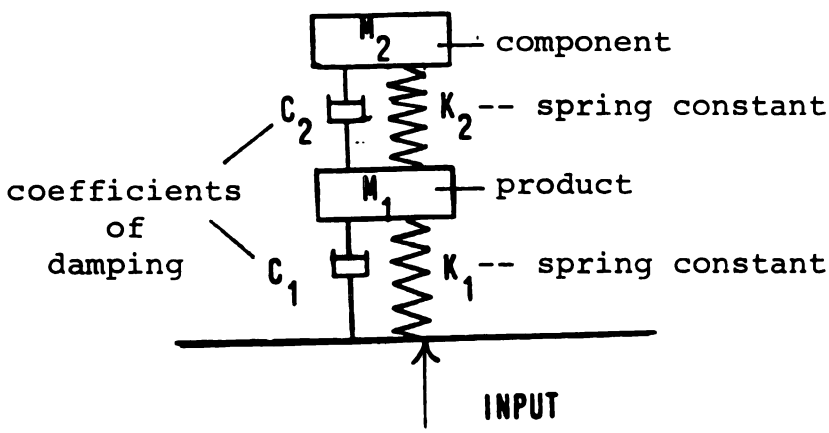


Figure A-3. Spring-mass system -- product and component.

Amplification of the input shock to the critical component can be described in Figure A-4.

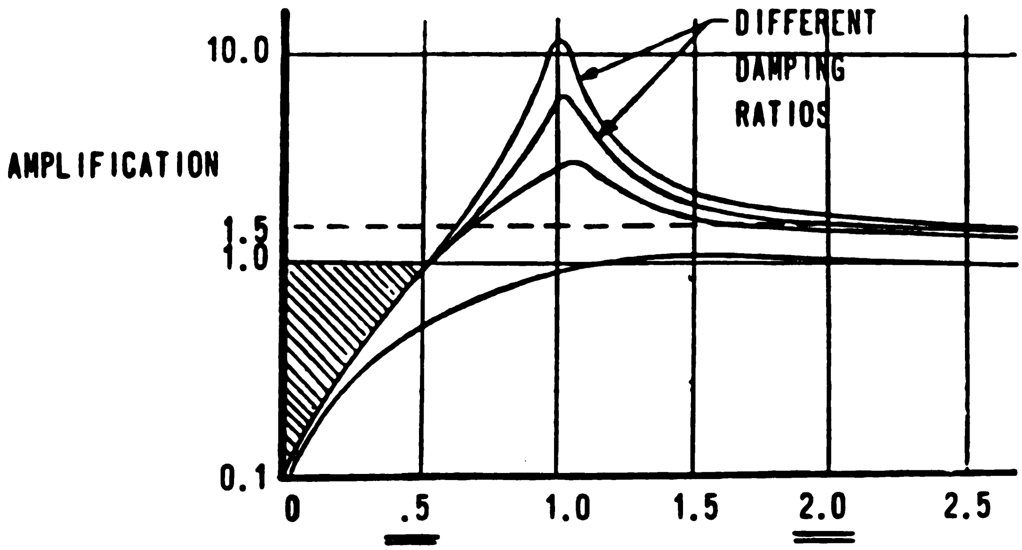


Figure A-4. Amplification of input shock.

APPENDIX B

DETERMINATIONS OF PEAK ACCELERATIONS

APPENDIX B

DETERMINATION OF PEAK ACCELERATIONS

Peak accelerations can be determined from PD values as follows:

$$PD = \frac{\sum_{i=0}^{i=N} (RMS)_i^2 / N}{BW} \; g^2/Hz \qquad \text{(from Chapter 2)} \quad (2.1)$$

PD = Power Density (g^2/Hz)
RMS = Root Mean Square acceleration (g's)
N = Number of data samples averaged
BW = Bandwidth of the filter (Hz)
(usually normalized to 1 Hz).

Any random phenomenon will generate a normal distribution of its values. In this case, the amplitudes of random vibrations are assumed to be randomly distributed about a mean value of zero. See Figure B-1.

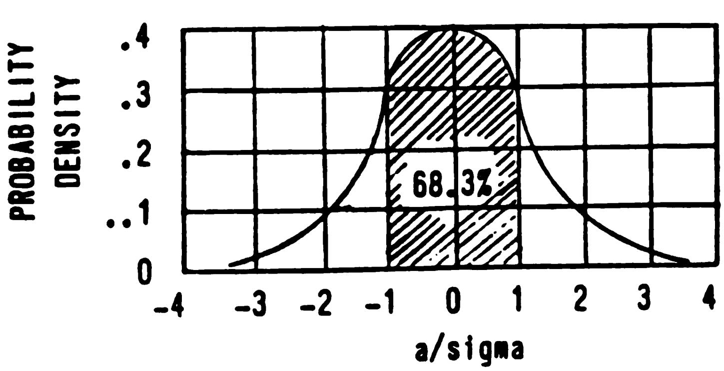


Figure B-1. Normal distribution of acceleration levels.

Distributions about the mean determine the level of energy present at any given frequency. The Root Mean Square (RMS) acceleration is then related to Power Density as the standard deviation is to the variance of a measured population. Therefore:

$$PD = (RMS)^2 = \text{variance}$$

$$\sqrt{PD} = RMS = \text{standard deviation}$$

It is possible to determine the range of peak accelerations at a given frequency by using the following procedure:

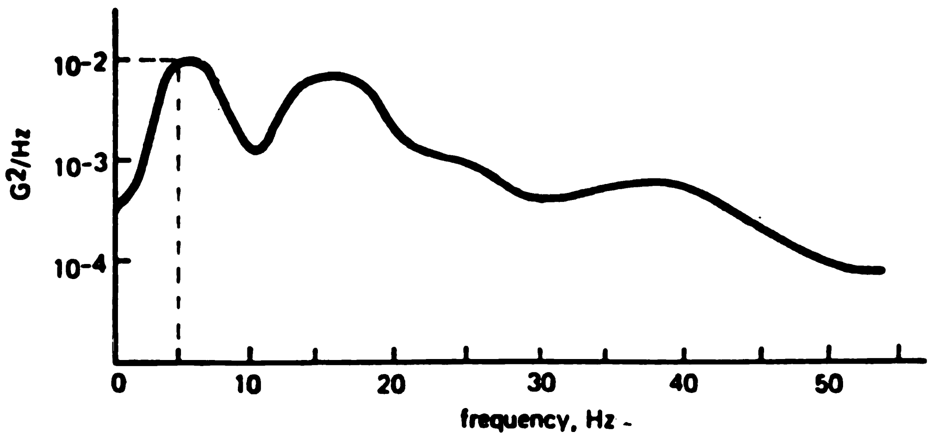


Figure B-2. Power Spectral Density plot.

At 5 Hz, the measured PD level is 10^{-2} g^2/Hz. Therefore:

$$\sqrt{PD} = 10^{-1}\ g = \text{RMS acceleration}$$

$$\text{RMS acceleration} = 0.707\ A_p \qquad (B.1)$$

$$A_p = \text{Peak acceleration (g's)}$$

$$A_p = 0.14\ g.$$

One standard deviation (one sigma from Figure B-1) for the distribution of acceleration amplitudes, would be ± 0.14 g. Three standard deviations would increase the range of values to ± 0.42 g. G_{RMS} occurs 68.3% of the time and does little damage. Three sigma accelerations occur only 4.3% of the time, but do most of the damage.

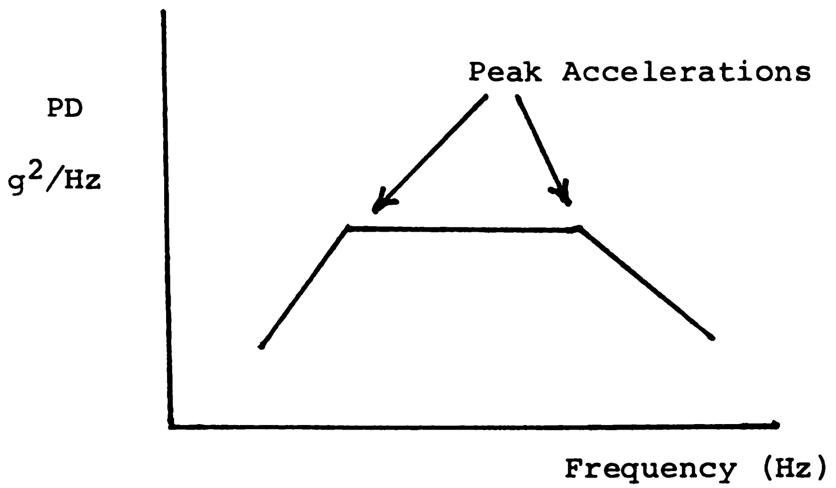


Figure B-3. Peak acceleration range.

The plot in Figure B-3 identifies the frequency range that has the highest energy level. This range may be chosen as a suitable test profile for products shipped in this environment.

APPENDIX C

MODAL ANALYSIS OF A TRUCK TRAILER FLOOR

APPENDIX C

MODAL ANALYSIS OF A TRUCK TRAILER FLOOR

In order to describe the responses of a truck trailer floor to vertical inputs from the physical distribution environment, it is necessary to perform a modal analysis.

C.1 Test Set-up

Trailer dimensions and mapping grid are shown in Figure C-1. A 38-foot Fruehauf trailer, model number FBX-F2-38, was chosen for measurement. It was grounded and had tire pressures ranging from 85 to 90 p.s.i.

C.1.1 Instrumentation Hardware

Test measurement apparatus consisted of the following:

B&K Force Transducer 8200

Force Hammer

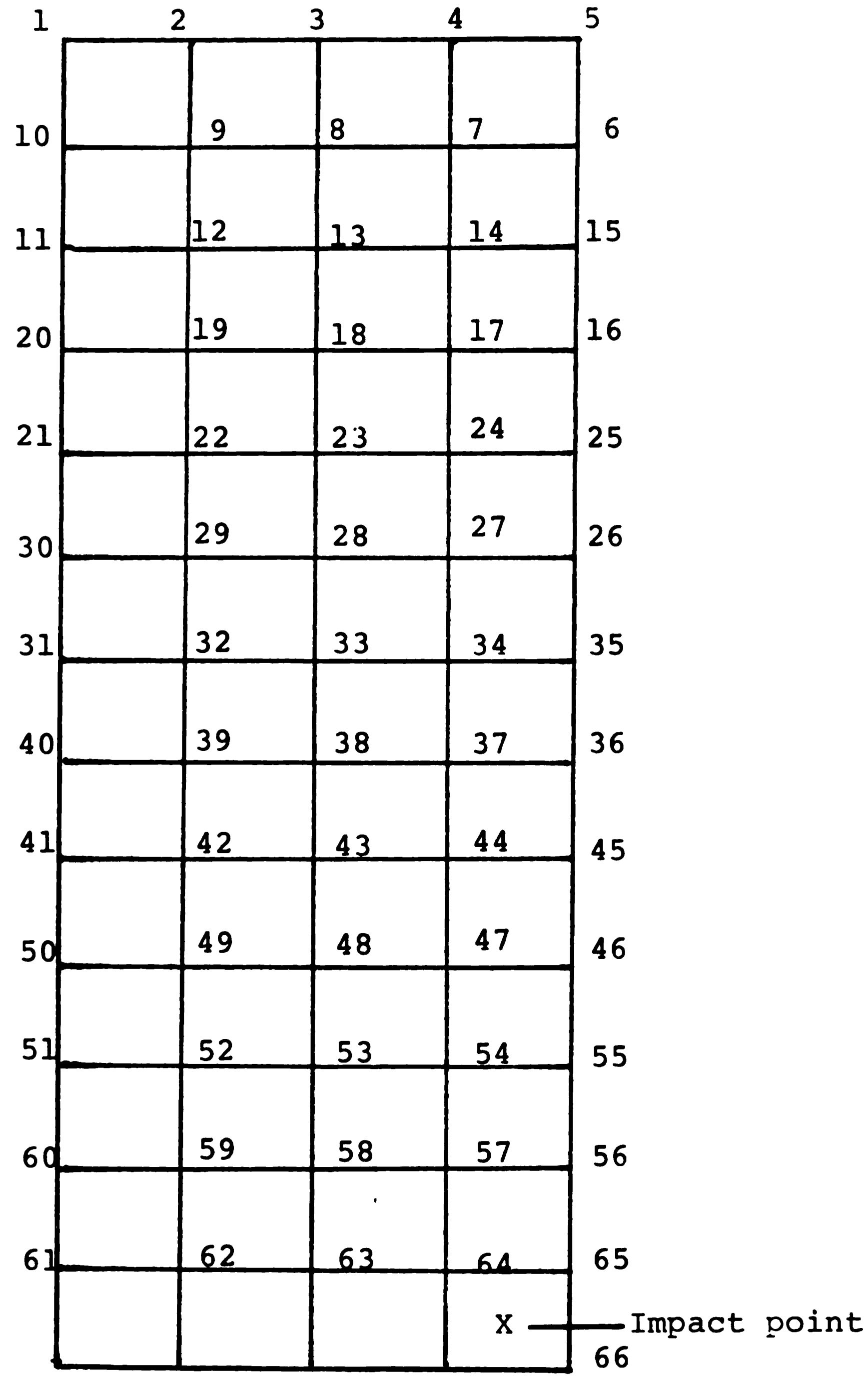
B&K Response Accelerometer 4369

B&K Conditioning Amplifiers (2) 2635

B&K Spectrum Analyzer 2035

Hewlitt-Packard Computer 9816/9121

The force hammer was a 5-lb. sledge, with a force transducer attached. A rubber tip was affixed to the end opposite the transducer, giving a frequency range of 0 to 500 Hz.



Trailer Dimensions: 38 ft. by 8 ft.
(Not to Scale)

Figure C-1. Trailer floor mapping grid.

C.1.2 Instrumentation Software

Structural Measurement Systems (SMS)

Modal 3.0, Version 4.0

Basic 3.0, Version 4.0

Figure C-2 shows the grid orientation with respect to the x, y, and z-axes. Numbering begins at point (0,0,0). The plane identified is the x-y plane. The display sequence will allow each mode to be defined separately.

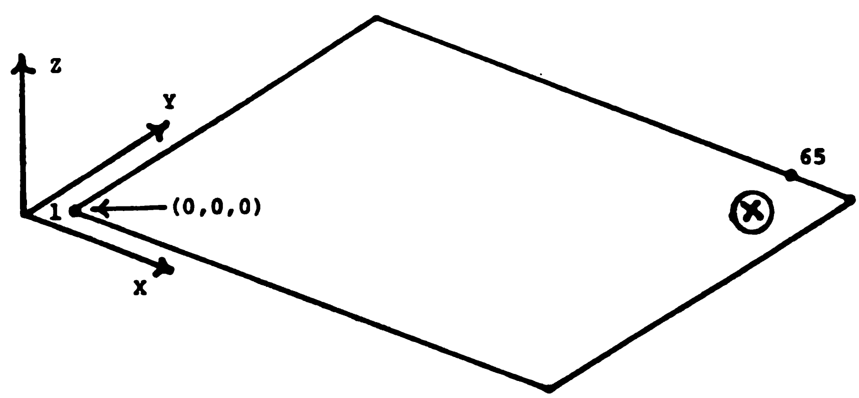


Figure C-2. Grid orientation.

C.2 Measurement Methodology

The point of excitation is indicated by the X symbol in Figure C-2. Instrumentation was set up as shown in the schematic in Figure C-3. An impact hammer was chosen for this test, as it is a field measurement study, carried out in a distribution center warehouse. It was not deemed possible to set up a vibration system, with stinger, to excite the floor resonances.

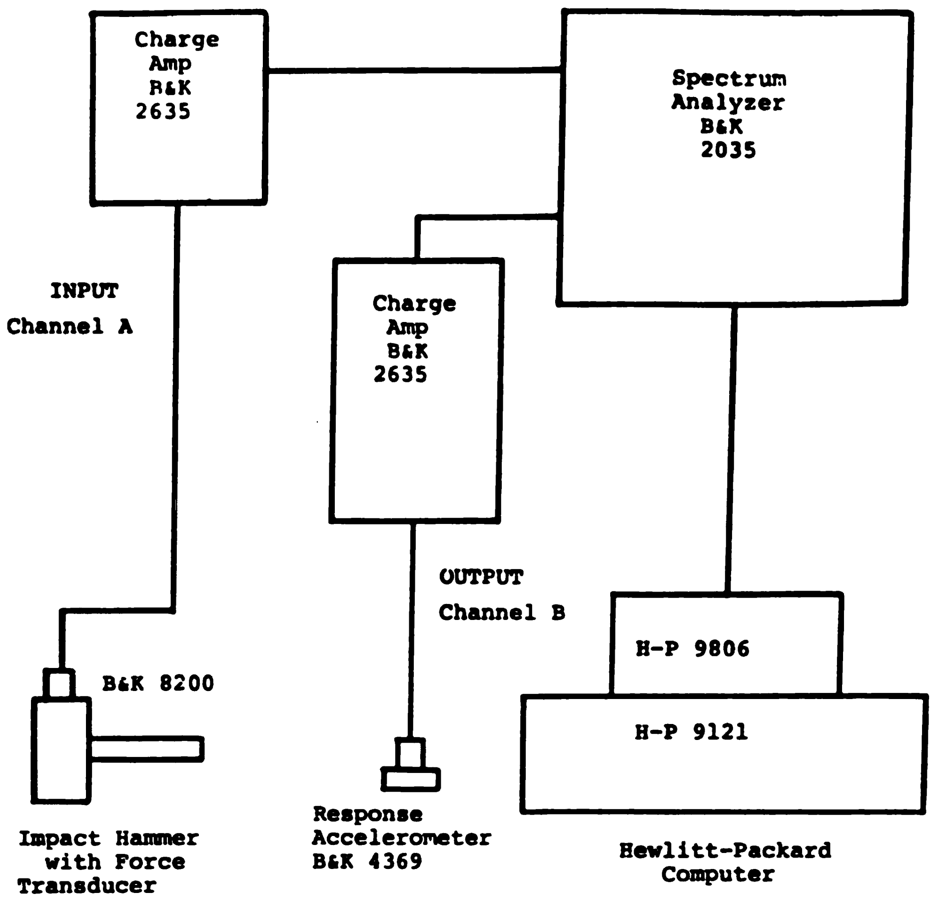


Figure C-3. Instrumentation schematic.

Preliminary testing with the impact hammer indicated sufficient energy to generate responses at each point on the grid. The accelerometer was moved, successively, from point 1 to point 65. Resonances were plotted with the spectrum analyzer, until each point's profile was distinct. A sample profile is shown in Figure C-4.

Initial calibration on the input channel was set at 3.16 mv/N. The output setting was 10.0 v/g. Adjustments were made, as required, during the data collection phase of the analysis. All calibration settings are noted in Table C-1. Table C-2 notes the various strong resonances encountered and the frequencies at which they occurred. Points 8,10 and 11, near the front of the trailer, demonstrated resonant responses in the 5 to 12 Hz range. From point 40 to 60, responses were noted in the 0 to 10 Hz catagory. It is thus determined that response frequencies are due to the nature of the trailer's suspension system.

C.3 Estimate Modal Parameters

The curve fitting procedure was accomplished in two steps. First, each profile was reviewed to determine whether single or multiple degree of freedom techniques were required. Figure C-5 makes such a comparison. Second, peak resonances were defined, and then curve-fit using one of the above techniques. Then the rest of the measurements were AUTOFIT, fitted to the same parameters.

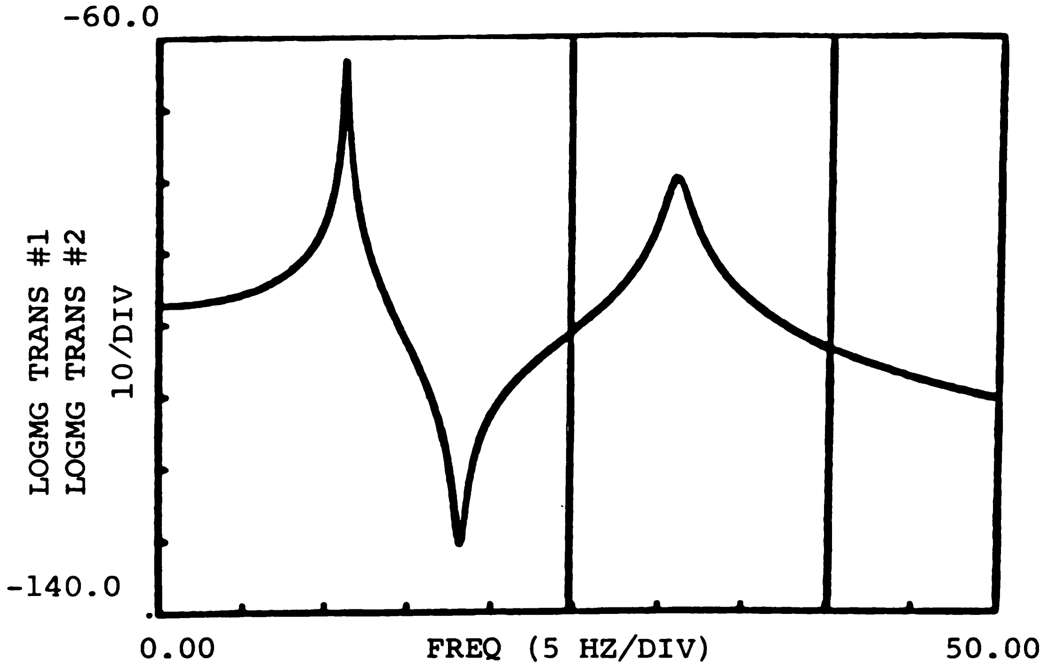


Figure C-4. Sample measurement.

Table C-1. Calibration Settings.

Initial Calibration:
Input (Channel A) 3.16 mv/N
Output (Channel B) 10.0 v/g

Point	Channel	Setting
6	A	1 mv/N
23	B	3.16 v/g
44	B	1.0 v/g
57	B	360 mv/g
66	B	21.6 mv/g

Table C-2. Resonances.

Point	Frequencies
8	5 Hz, 8 Hz
10	5 Hz, 12 Hz
11	11 Hz, 12 Hz
24	0 to 10 Hz
41 to 60	0 to 10 Hz

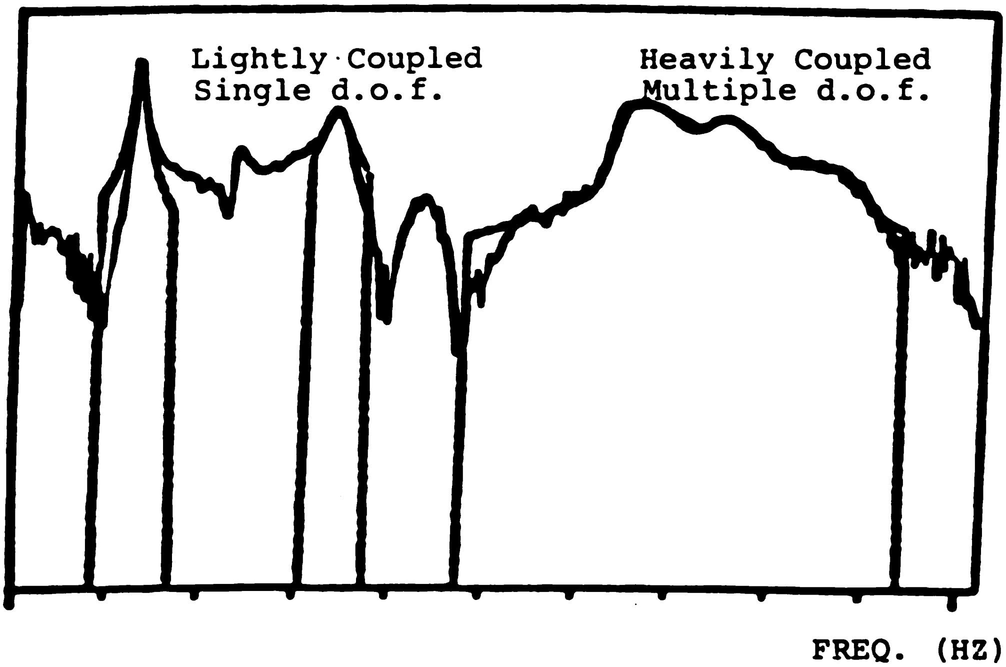


Figure C-5. Combining SDOF and MDOF methods.

C.4 Sort Modal Data

A sorting process was used to generate the necessary mode shapes. An example, showing frequencies and damping levels, is given in Table C-3. The mode shapes were transferred into global coordinates.

C.5 Display Mode Shapes

The structure can be shown in animation. Each mode can be viewed separately. Inferences can be drawn from the animation that pinpoint potential problems with cargo placement.

Table C-3. Modal Frequency and Residue (Sample).

*** FREQUENCY AND DAMPING ***

	FREQ(HZ)	DAMP(%)	DAMP(HZ)
1.	7.52	9.17	5.37
2.	10.78	.60	2.41

APPENDIX D

PSD PROFILES: TOFC AND CIWC

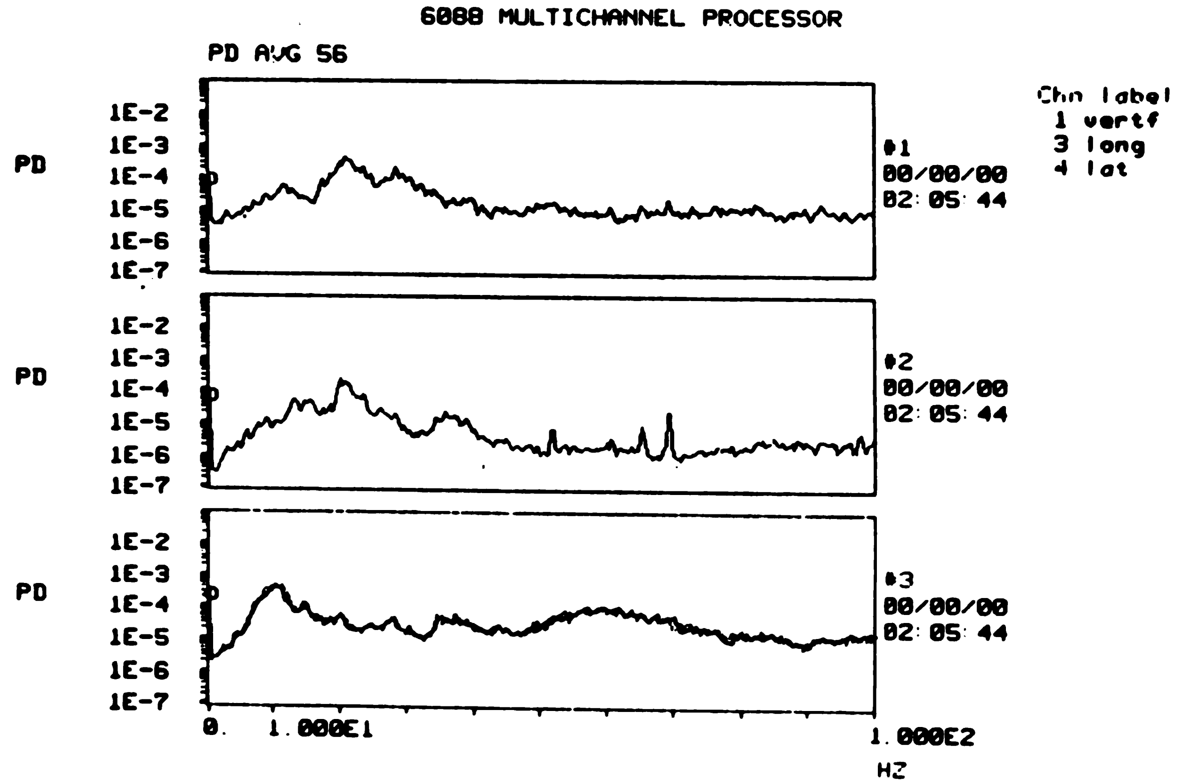


Figure D-1. PSD plots - TOFC.

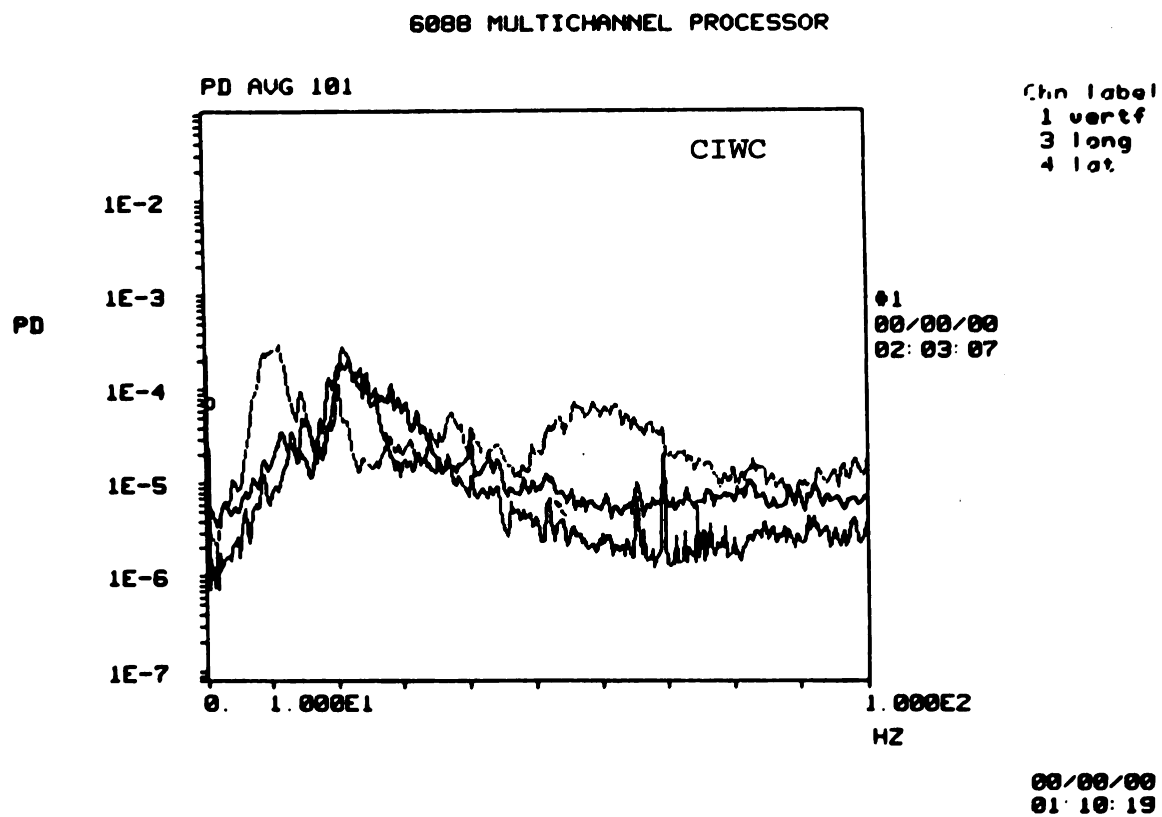


Figure D-2. PSD overlay.

APPENDIX E

SHOCK DISTRIBUTION: TOFC AND CIWC

DATA SAMPLES

Table E-1. Test Report.

VEHICLE TYPE: TOFC/Container-in-a-Well Car

TRANSDUCER POS: Longitudinal Axis (Disk 2)

DISTRIBUTOR: Conrail/NW/Union Pacific

FROM: Rochester, NY

TO: Whittier, CA

RESULTS	AVERAGE ACC,g	STD DEV ACC,g	AVERAGE DUR,ms	STD DEV DUR,ms
LOCATION 1	7.87	2.95	2.06	1.90
LOCATION 2	8.16	1.81	1.60	0.81
LOCATION 3	6.71	3.00	2.70	3.41
LOCATION 4	3.33	2.13	5.81	3.18
LOCATION 5	2.87	2.19	6.78	3.62
LOCATION 6	9.81	6.16	2.80	2.53

SHOCK DIST. RANGE, g's	NUMBER OF OCCURRENCES	PERCENT
0-1	1	1%
1-2	18	12%
2-3	28	19%
3-4	11	7%
4-5	9	6%
5-6	2	1%
6-7	9	6%
7-8	17	11%
8-9	21	14%
9-10	11	7%
10-11	6	4%
11-12	4	3%
12-13	3	2%
13-14	1	1%
16-17	1	1%
17-18	5	3%
18-19	3	2%

SUMMARY: TOFC from Roc to Chi, Cont. in Well Car Chi to Whittier
Conrail Roc to Chi, NW Chi to Freemont NE,
Union Pacific Freemont to Whittier

Threshold 2 g

Table E-2. Shock data sheet.

Component	DAY	HR	MIN	Velocity	Acceleration m/sec2	Correction Factor	Actual Velocity	Shock Duration seconds	Shock Duration millseconds	Acceleration g's	Data Dist	Numbe Occu
Location 1	3	19	58	0.11	24	1.0035	0.1104	0.0072	7	2.4465	0	
	3	19	59	0.07	80	1.0003	0.0700	0.0014	1	8.1549	1	
	3	19	59	0.08	73	1.0004	0.0800	0.0017	2	7.4414	2	
	3	20	0	0.07	80	1.0003	0.0700	0.0014	1	8.1549	3	
	3	20	0	0.1	93	1.0002	0.1000	0.0017	2	9.4801	4	
	3	20	1	0.07	80	1.0003	0.0700	0.0014	1	8.1549	5	
	3	20	1	0.07	77	1.0003	0.0700	0.0014	1	7.8491	6	
	3	20	21	0.03	23	1.0038	0.0301	0.0021	2	2.3445	7	
	3	20	25	0.07	110	1.0002	0.0700	0.0010	1	11.2130	8	
	3	20	26	0.07	20	1.0050	0.0704	0.0055	6	2.0387	9	
	3	20	28	0.07	130	1.0001	0.0700	0.0008	1	13.2518	10	
	3	20	31	0.1	80	1.0003	0.1000	0.0020	2	8.1549	11	
	3	20	31	0.08	68	1.0004	0.0800	0.0018	2	6.9317	12	
	3	20	31	0.07	80	1.0003	0.0700	0.0014	1	8.1549	13	
	3	20	32	0.07	93	1.0002	0.0700	0.0012	1	9.4801	14	
	3	20	32	0.07	120	1.0001	0.0700	0.0009	1	12.2324	15	
	3	20	33	0.1	19	1.0056	0.1006	0.0083	8	1.9368	16	
	3	20	34	0.07	60	1.0006	0.0700	0.0018	2	6.1162	17	
	3	20	34	0.07	76	1.0003	0.0700	0.0014	1	7.7472	18	
	3	20	35	0.04	89	1.0003	0.0400	0.0007	1	9.0724	19	
	3	20	35	0.07	75	1.0004	0.0700	0.0015	1	7.6453	20	
	3	20	35	0.08	85	1.0003	0.0800	0.0015	1	8.6646	21	
	3	20	35	0.07	85	1.0003	0.0700	0.0013	1	8.6646	22	
	3	20	35	0.07	100	1.0002	0.0700	0.0011	1	10.1937	23	
	3	20	35	0.07	110	1.0002	0.0700	0.0010	1	11.2130	24	

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