AN ASSESSMENT OF THE COMMON CARRIER SHIPPING ENVIRONMENT

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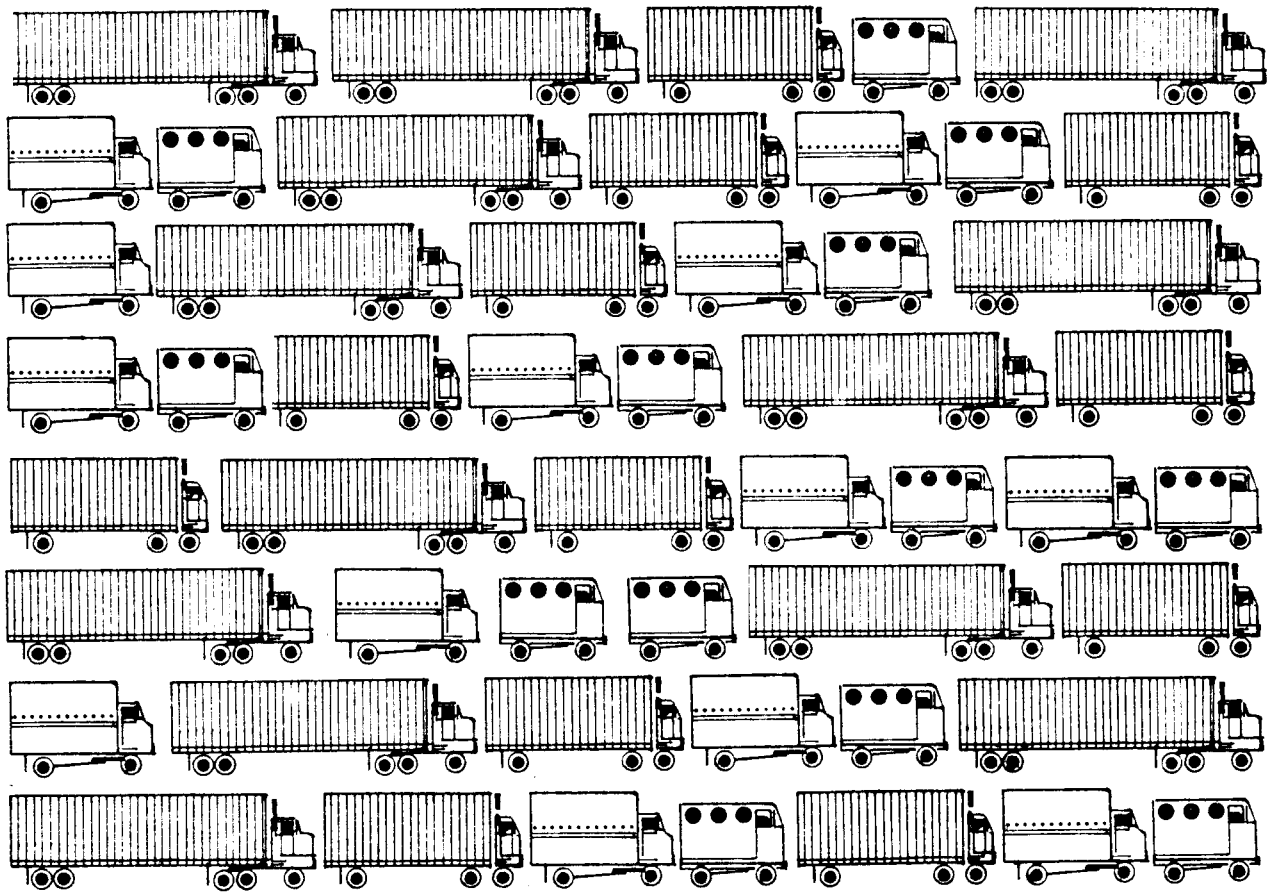

ABSTRACT

An assessment of available data and information describing the common carrier shipping environment was conducted. The assesment included the major shipping hazards of shock, vibration, impact, temperature, and humidity associated with the handling, transportation, and warehousing operations of typical distribution cycles. Previous environmental studies and current data are reviewed and assessed for applicability to general type cargo design and/or evaluation. The data for each hazard are summarized in a format considered most useful to packaging engineers when such data are available. Hazards requiring further information and description are identified and discussed.

PREFACE

This study was conducted by GARD, Inc., in cooperation with the USDA Forest Products Laboratory under research agreement 12-49, with Fred E. Ostrem, Senior Engineer, as principal investigator. The technical coordinator for the Forest Products Laboratory was W. D. Godshall.

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INTRODUCTION

Packaging in all its forms consumes tremendous quantities of wood-based products, including paper, paperboard, and wood. Because of these quantities, there is the potential for substantial savings of wood through more efficient and effective use of these wood-based products. Proper use of these materials will not only ensure protection of the product being shipped at the lowest cost, but will extend and conserve one of our natural resources.

Wood-based products are used in a variety of forms in packaging, ranging from the internal cartoning or cushioning to the outer fiberboard container including unit load platforms or pallets. Efficient and effective use of these products implies that there is no waste either in the form of excessive packaging (overpackaging) with resulting high material costs, or inadequate packaging, with resulting product loss or damage. Loss and damage is a highly visible cost and statistics will generally indicate this to be an area for improvement. Overpacking is a much more difficult condition to identify and cost, except for obviously high packing costs. However, it can be assumed that this is also an area for improvement. The desired goal is to design a packaging system which will provide adequate protection, but at the lowest possible total cost.

The major inputs required for efficient and effective use of packaging materials include: (1) a knowledge of the shipping or operating environment, (2) a knowledge of the fragility or resistance to damage of the item to be protected or packaged, and (3) a knowledge of performance

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1/ Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

or protective characteristics of the packaging materials. Unless adequate and accurate design information of this type is available, alternate, more costly and time consuming approaches must be adopted, e.g., trial shipments. This study is concerned with assessing information with respect to the shipping environment and more specifically, the common carrier shipping environment. Previous studies have dealt with this same problem area, but for various reasons, have included information or data not considered applicable to the common carrier distribution environment. Addition data have been generated which require review, evaluation, and incorporation for improved descriptions. Finally the shipping environment needs to be defined in terms applicable to general type cargo and suitable to packaging-related problems. Associated with the descriptions is the identification of gaps in available information. Future research effort can thus be directed and concentrated more effectively in the appropriate area.

Accurate and detailed descriptions of the shipping environment are important, not only for design purposes, but as background informaton, for the development of performance tests to verify a design, and for the development of realistic material specifications.

The following are the author's assessments of the availability and adequacy of data and information defining the hazards encountered in the common carrier shipping environment.

SHIPPING ENVIRONMENT HAZARDS

The common carrier shipping environment is defined to include all of the environmental conditions likely to be encountered by cargo during movement in typical distribution cycles from the point of manufacture to the ultimate consumer. These movements include transportation by common carrier motor freight truck, railcar, aircraft, and ship. The conditions of interest are related to the physical requirements of the shipping container associated with different segments of the distribution cycle including handling (loading and unloading), vehicle transport, warehousing, or storage. The conditions of interest include shock, vibration, impact, compression, and the climatic conditions of temperature and humidity.

The data and information describing the shipping environment have been reported in a variety of forms, depending on the end-use of the data, instrumentation available, data reduction equipment, etc. In addition, the data cover a variety of transport systems and distribution cycles ranging from special transporters to military supply channels. Thus, available data need review to determine their applicability to the common carrier shipping environment and summarization in a format suitable for package design and/or evaluation.

A previous study (37)[2/] summarized most of the available information describing the shipping environment. Much of the information contained in that report is still applicable today, but requires further review and evaluation. In addition, new studies have been conducted, many of which are directly applicable to the common carrier shipping environment. However, as in previous studies, the specific objectives of these new programs varied, the data reduction techniques varied, or the data format varied, making correlation and evaluations difficult. Nevertheless, all available information has been reviewed and assessed for its applicability to general cargo shipments. In most instances, the new data have been found to correlate well with previous descriptions and fill in some previously identified data gaps. The formats selected for data presentation in this report have been based on the desire to have the information in a form that will have the broadest possible application based on current package design practice and package test equipment.

References are cited for those desiring more detailed and specific information on a particular hazard. Ostrem, et al. (37) reports on the results of a field study to determine the causes and nature of damage incurred by corrugated containers shipped by rail. Based on examination of more than a million containers, only 1.1 percent of the containers were damaged, and merchandise in only 0.33 percent of the total was damaged enough to cause claims. Of the damage containers, 10 percent involved punctures and 66 percent involved crushing. Inadequate bracing and doorway blocking accounted for 33 percent of the damage attributed to shippers, while rough handling accounted for 80 percent of the damage attributed to carriers. Results of surveys of this type would identify the hazards requiring immediate attention.

HANDLING

Handling occurs at the loading, unloading, and transfer points and can occur as a result of either manual or mechanical handling operations. They are generally considered to impose the severest loads on cargo.

The loads imposed on cargo during handling operations have historically been reported in terms of height-of-drop. The height-of-drop or drop height refers to the vertical distance from the ground or impact surface that the container is released (either intentionally or accidentally) and falls under the influence of gravity.

2/ Underlined numbers in parentheses refer to literature cited at the end of this report.

Drop height data have been collected by several methods (observation, camera, instrumented package). The instrumented package is considered the most effective technique for gathering data on the many handling operations of a typical distribution cycle. Instrumented studies are performed with an instrument located inside a package and calibrated to record actual drop heights. In past studies using instrumented packages, the data have not been separated or segregated with respect to individual handling operations. The data can only be separated if the instrument has an internal time mechanism and the package location is time-related. Normally this is not the case, therefore instrumented drop height data have not been correlated with particular handling operations.

Available Data

Typical drop height data from two separate instrument measurement studies are shown in figure 1. These data represent the results of two of the most extensive measurement programs conducted in the United States. Curve A applies to shipments of 43-pound cleated plywood boxes and represents data from a Air Force study (8) of their supply channels involving primarily Railway Express shipments. Curve A represents data from 49 trips, using 13 packages and 15 recorders. Curve B applies to a more recent study by the U.S. Army Natick Development Center (6) involving shipments of 25-pound fiberboard boxes. The Natick study is based on a compilation of data from numerous shipments via truck, aircraft, Parcel Post, United Parcel Service, and overseas shipments aboard Navy ships. The latter shipments were made with the package positioned at the bottom center of a unitized load, using 15 packages on 80 trips. It is reported that the data base was not broad enough to describe the effect of a particular distribution cycle (i.e., UPS, truck, ship, etc.).

The preceding data are plotted on log probability paper and indicate the percentage of drops over indicated drop heights. The data show, for example, that only one package in 100 (1 pct probability) was dropped from a height greater than 58 inches for the 25-pound container and 30 inches for the 43-pound container. Although completely different instrumentation was used to record data for each study, the data show good correlation with regard to drop height probability and package weight. Similar type data are available from studies conducted in Europe (2) for package sizes ranging from 40 to 500 pounds, and are summarized in figure 2. These data are based on rail shipments, although portions of the shipments were by road. Only three drop heights were recorded, since previous studies had established the straight line relationship of the data when plotted on a probability plot. The same trend in distribution of drop heights as reported in U.S. studies is apparent as is the influence of package weight. Drop height data from

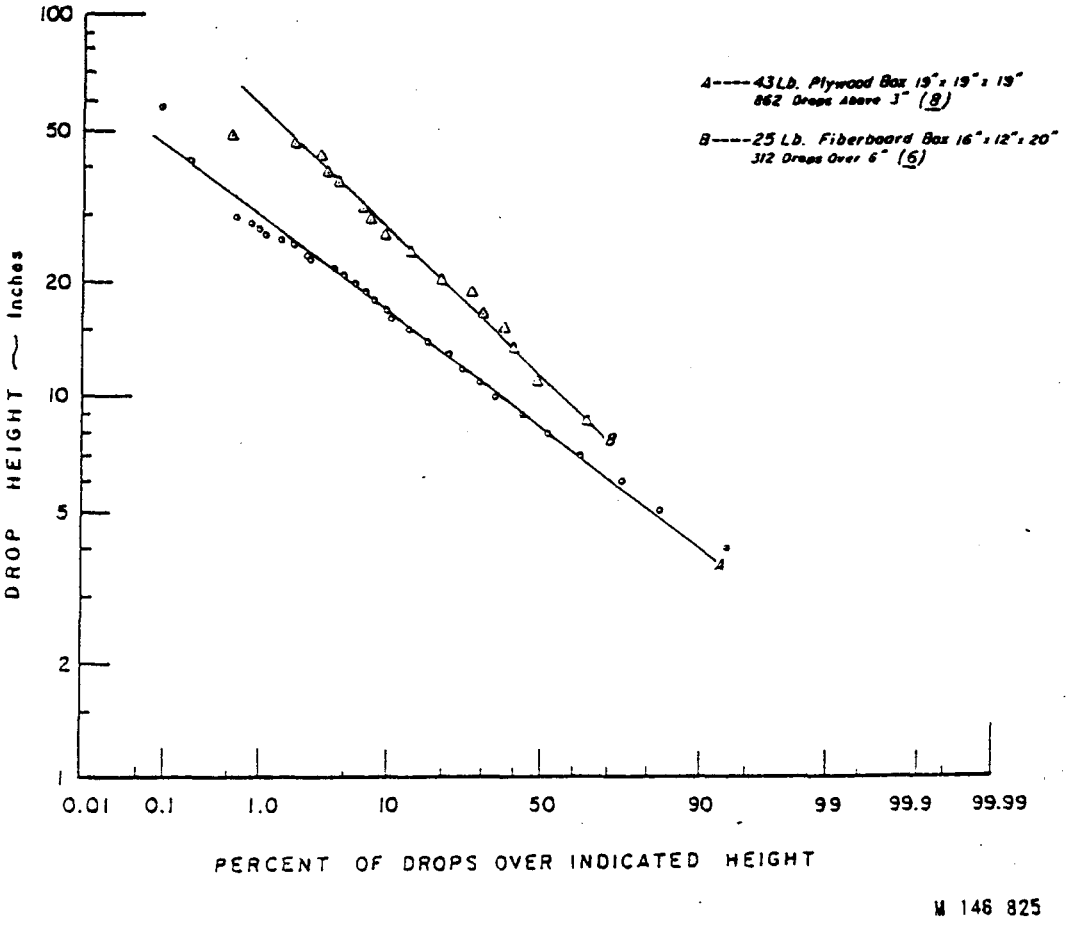

Figure 1. --Drop height versus probability of occurrence (U.S. Studies).

European studies of overseas shipments is reported (2). Data from European studies for specific handling operations, e.g., transferring packages from a railroad car to a handcart, sorting packages according to destination, and unloading and stacking packages is summarized (36).

The data for drop heights can also be plotted to show the number of drops recorded at the different heights. Figures 3 and 4 are replots of the data presented in figure 1. Again, there is good correlation between the studies showing a large number of low-level drops and very few drops at the higher levels.

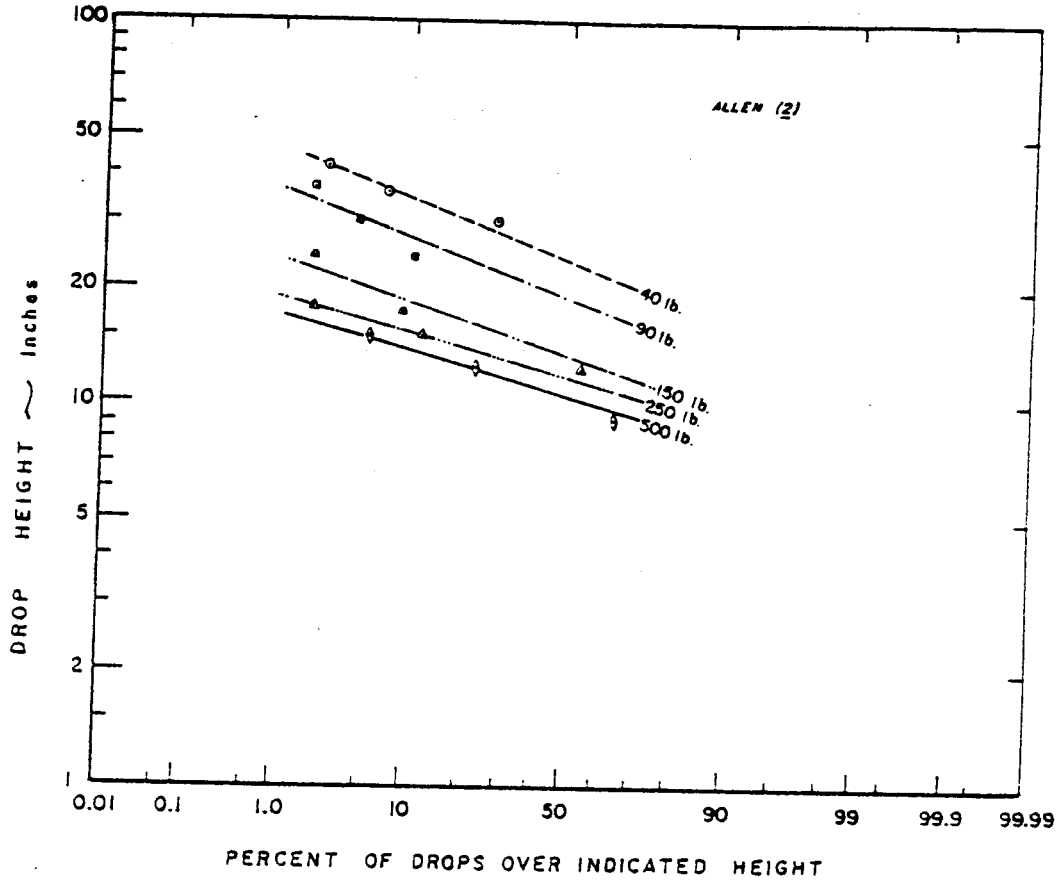

Figure 2. -- Drop height versus probability of occurrence (European Studies) (Allen (2)).

Additional information resulting from teh Natick study relates to the surface of the package which first impacts the gournd, i.e., the angle of impact. Teh data showed: (1) the container bottom surface received the majority, 70 percent of all the drops, and (2) edge and corner drops occured from much greater heights than the flat drops. Distribution of drops were: 80 percent bottom and top surfaces combinded, 12 percent front and back surfaces, and 8 percent side surfaces. Simlar data are presented (36) on the distribution of drops reparted from European studies. In addition, information is presented to show the effects of labels, distribution mode, handholds, and package size and weight.

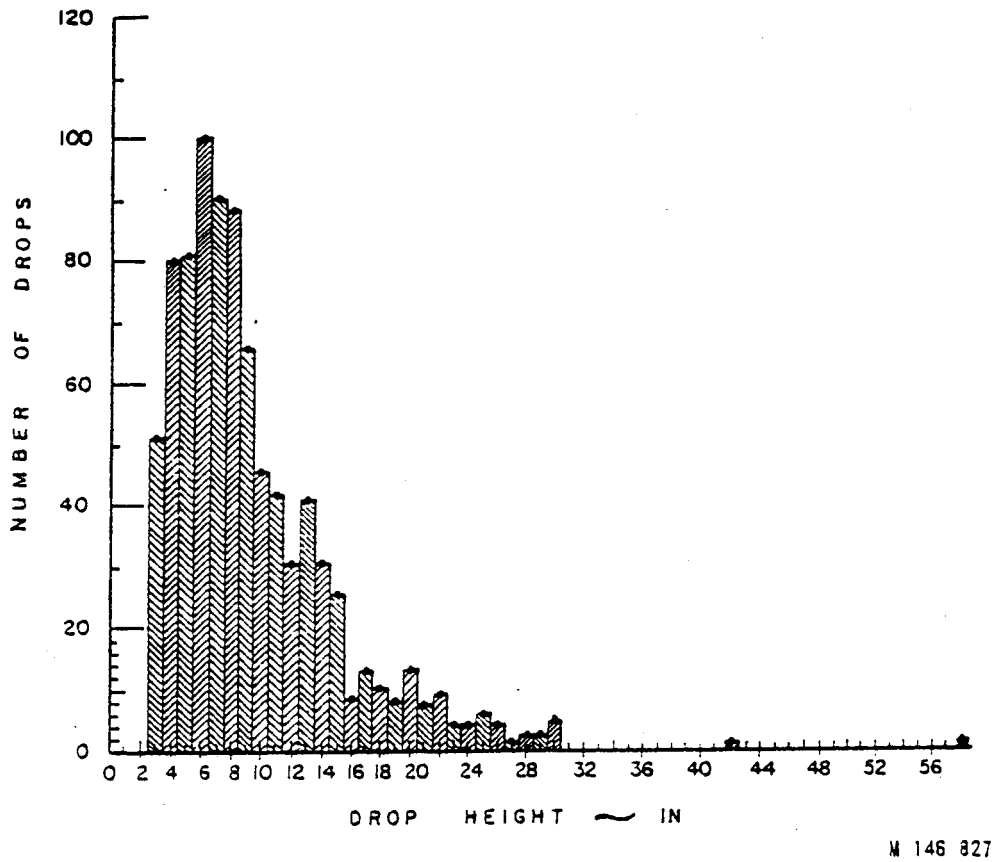

Figure 3. --Drop height versus number of drops (43-lb. container).

Assessment of Handling Data

The available data on manual handling operations provide an indication of the variability and random nature of the drop hazard and show the general effect of certain package characteristics, such as size, weight, handholds, labels, and the distribution cycle. The effect of most of these characteristics, however, is based primarily on data from European studies and any assumptions regarding similarity to U.S. operations is subject to question. Direct comparisons of drop height data from the two U.S. studies with data from European studies show the same general trend regarding the effect of package weight and the distribution of drops, but the drop heights and probability levels are significantly different.

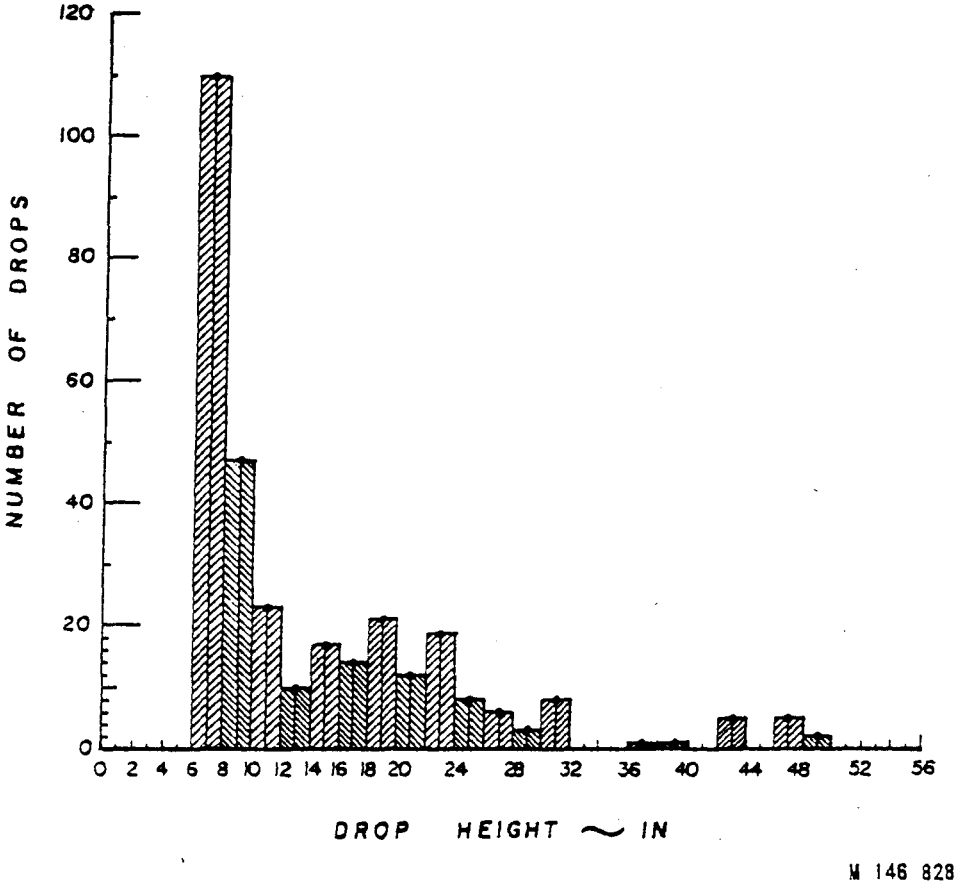

Figure 4. --Drop height versus number of drops (25-lb. container).

The reasons for the difference in drop heights and probability levels are not clear, but could be caused by a number of factors including a difference in data reduction procedures, and/or a difference in the sensitivity of the instrumentation, particularly for angle drops. It is difficult to imagine a difference due to a basic difference in the handling operations. Further European studies have for the most part reported data in terms of drop heights for individual handling operations or specific distribution cycles. United States studies have not followed this procedure, since the objective in most of these studies has been to establish the severest or maximum drop heights.

Although commonly used distribution cycles have been included, the two U.S. studies concentrated on military supply channels, and specific container sizes and weights. How applicable these data are to common carrier operation is unknown. Further, the data have been presented as a compilation of data from numerous handling operations. The data have not been segregated with respect to the individual handling operations, e.g., forklift, manual handling, crane, etc., nor with respect to manual or automated operations. Unless it can be shown that the data are representative of handling loads for common distribution cycles, the usefulness of the data is questionable. Additional information is needed to provide a much broader data base and to show the effect of the various distribution modes, specific handling operations, and container characteristics, including size, weight, labels, and handholds for the common carrier shipping environment.

Another area lacking documentation is the concentrated load application that occurs when one package is dropped on another. Various organizations have developed tests to produce this hazard, but there are no data to justify the shape, weight, or height of drop of one container onto another or of a simulated puncture projectile.

The available data concerning handling, although not adequate for package design or test purposes, do provide useful information. The data show, for example:

1. The probability of a package being dropped from a high height is minimal.

2. Most packages receive many drops at low heights while relatively few receive more than one drop from the higher heights.

3. Unitized loads are subjected to fewer and lower drops than individual packages.

4. Most packages are dropped on their bases. In most studies, base drops have averaged over 50 percent of the total number of drops.

5. The heavier the package, the lower the drop height.

6. The larger the package, the lower the drop height.

7. Handholds reduce the drop height by lowering the container relative to the floor during handling.

8. Labels such as fragile and handle with care have some effect, but can be considered minor.

Some of the preceding results could have been determined intuitively. In many instances, maximum drops are estimated by considering the size and weight of a package and relating it to typical types of handling. The drop height for an item carried by two men, for example, is 30 inches based on the distance from the floor to the downward extended arms of the men.

A major reason for the very sparse data has been the unavailability of a low-cost, self-contained instrument capable of recording drops over an extended time period. The Natick Drop Recorder (52) was developed to provide the required instrumentation and has been used successfully in the field (6). It is reported, however, that this equipment cannot be placed in the hands of untrained personnel and that the state of the art in solid state electronics has advanced to the point where this instrument is now obsolete. The Air Force Packaging Evaluation Agency has developed under contract a new solid state device that records drops in terms of incremental acceleration levels (g levels) (53). A brief Air Torte study in which the instrument was calibrated wthin standard reusable Air Force packages (Star Packs) to provide verification of drop height design values is reported (7). The instrument used in this program will soon become commercially available and represents the state of the art in instrumentation for measuring drop, heights.

Measurements of loads imposed on cargo as a result of mechanized handling are sparse. Barca (6) reports data for the 25-pound container included forklift, cargo net, conveyor sorting, and semi-automated depot operations, as well as manual handling, but does not separate the data. Gens (19) reports data recorded on four commercial type forklift trucks, but presents the data in terms of shock response. The shocks resulting from lifting and lowering the load on the forks were recorded, but were reported to be much lower than other sources recorded, particularly the shock caused by a bump in the test course. Additional studies are required to better define the mechanical handling hazard.

VIBRATION

The vibration environment has been studied in greater detail than any other shipping hazard. The interest is probably due to the fact that there is generally very little control over the operation of commercial vehicles and the resulting vibrations transmitted to the cargo. Another is the fact that the severity or level of vibration cannot be determined without a sophisticated and detailed measurement study. Vibration data resulting from the various studies have been reported in various forms. These forms vary significantly and are related to the end-use of the data and available data analysis equipment. They range from Power Spectral Density (PSD), peak acceleration versus frequency, overall

root-mean-square (rms) acceleration, rms acceleration versus frequency, and distribution of acceleration peaks within selected frequency bands. The reported acceleration levels, regardless of the format in which they are presented, are dependent on the filter bandwidths used in the analyses. Filters are used to separate the complex multifrequency signal into discrete frequency bands and are broadly classified as proportional or constant bandwidth filters. Proportional filters are proportional to their center frequency and accordingly provide high resolution at low frequencies and poor resolution at high frequencies. Typical proportional filters include octave (bandwidth 71 pct of center frequency) and one-third octave (bandwidth 24 pct of center frequency). Constant bandwidth filters use the same bandwidth regardless of center frequency and, thus, resolution is the same at all frequencies.

Modern analyzers use constant bandwidth measurements and techniques such as compression real-time analyzers (RTA) and fast Fourier transform (FFT) analyzers for rapid analysis. Both of these techniques produce the same results. These analyzers take snapshots of the amplitude-time history and produce amplitude frequency spectra at a rate dependent on the frequency resolution required. Each spectra is then averaged to produce an averaged spectrum. Most recent investigations have used this method. Filter bandwidths have varied, but are typically in the l-hertz range. The analyzer outputs also vary, but data are typically presented in terms of Power Spectral Density (g^2/Hz). This format is considered by many to be the only one suitable for describing random vibration. It can be used as a test specification or it can be used for analysis.

The primary advantage of a modern spectrum analyzer and the reason for its extensive use is its ability to rapidly and automatically analyze a complex signal and reduce or resolve it into basic components, i.e., frequency and amplitude. Large amounts of data can be analyzed in a very short time. Harris et al. (23) present a detailed discussion of data reduction procedures.

Truck Data

The more extensive measurement programs with regard to road vehicles have been conducted by Foley of Sandia (15), Schlue of JPL (44), Silvers of Westinghouse (48), and Kusza and Sharpe of MSU (47). The last three have been concerned with tractor-trailer combinations while Foley's studies have included flatbed trucks and vans.

Schlue's data are exclusively concerned with air ride suspension semi-trailers transporting spacecraft. The trailers used were typical commercial vans having a tandem rear axle system and air bag suspension. Vibration data are reported for different vans operating over smooth and

rough roads and for several locations within the van. These data are summarized to show the maximum, 95- and 50-percent levels of shock spectra and power spectral densities. A second study (45) was conducted to show the variation in vibration levels that can occur between two supposedly identical vans. One van showed high energy in the high frequency range and greater excitation along the nonvertical axis. The difference was attributed, not to the design of the systems, but to the condition of the systems. Rework of the poorer van's suspension brought it into compliance with what was considered nominal performance. Maximum, 95- and 50-percent PSD levels computed from 37 PSD plots are presented. The curves include rough roads, smooth highway, and several loading conditions ranging from light to normal load.

Kusza and Sharpe report vibrations recorded on scheduled common motor carrier semitrailers. Three different trucks with cargo weights of 26,500 pounds (43,507 lb with trailer) for a 45-foot trailer, 6,000 pounds for a 40-foot trailer, and 9,000 pounds for a 40-foot trailer, were studied. A fourth trailer (30 ft) making local deliveries and starting with a load of 4,900 pounds (the load decreased as deliveries were made) was also investigated. Except for transients, the fourth trailer was reported to exhibit the lowest vibration levels. The data for all trailers showed the rear vertical to be the severest. The front-vertical vibration levels were between the levels recorded at the mid and rear. Lateral measurements were smaller by a factor of two or more. Trucks with light loads were reported to have a lower level of vibration independent of speed. Speed increased the levels of bibration in all cases. Power spectral density's summarizing the rear vertical measurements for all runs are presented, as are PSD's showing the effect of speed, location, and direction.

Silvers (48) reports on studies at Westinghouse Electric Corporation to determine the vibration environment in tractor trailers. Tests were conducted to determine the effect of suspension system (conventional steel spring, rubber isolator, damped coil springs, and air bags), degree of load, rear wheel position, road type, and driver. The worse ride with regard to road type was reported to occur during high speed operation on interstate highways. With regard to location and weight, the worst ride was reported to occur over the rear axle for a lightly loaded trailer. The individual drivers had little effect on the vibration levels. In all cases, a 3-minute segment of data recorded during operation on a high speed beltway was analyzed. In some cases, a 0.2-hertz bandwidth resolution was used and the data analyzed from 0.2 hertz to 50 hertz. In other instances, a 1-hertz bandwidth was used and the data analyzed to 250 hertz.

Foley (15) reports on data recorded on seven different trucks ranging from well-used tractor-flatbed trailers with conventional leaf-spring

suspensions to new tractor-van trailer systems with air ride suspensions. In addition, 2-1/2-ton flatbed trucks of conventional design and a special design for transporting explosives were included. Load ranges, i.e., cargo load, varied for some vehicles and were fixed for others. The data have been summarized by an envelope PSD curve which covers all vehicles and load conditions investigated. Sources of information used in the description are given in (16). Much of these data have been summarized previously (37) in the form of envelopes of acceleration versus frequency and their probability of occurrence. A typical summary plot for a 2-l/2-ton truck is shown in figure 5. The original data were presented in two formats designated as individual and composite. The individual format presented the data for particular road and operating conditions (e.g., four-lane highway, construction zone, crossing railroad tracks), while the composite format statistically combined the data for the various conditions or events to arrive at a description characterizing an entire trip. The advantage of the statistical format shown in figure 5 is that it-presents not only the peak values, but the distri-

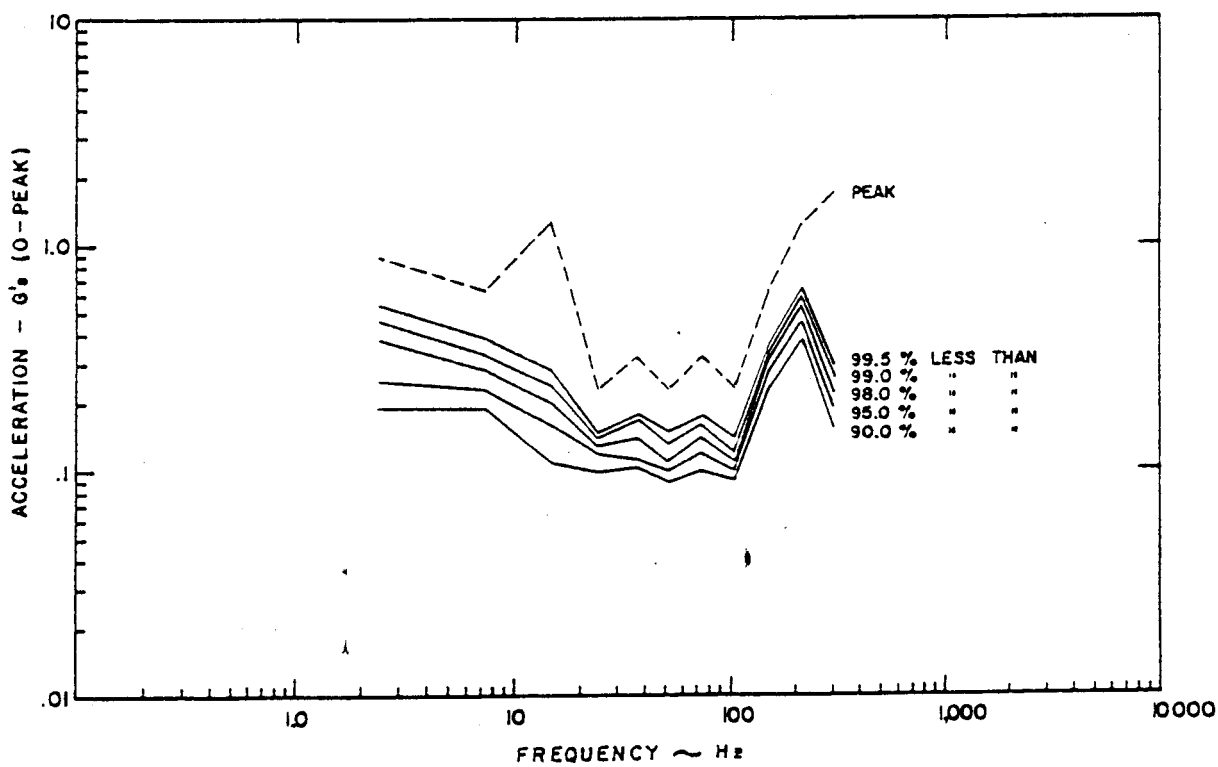

Figure 5. --Frequency spectra for various probabilities--2-l/2-ton flatbed truck (vertical direction, composite of normal conditions).

bution of accelerations below, the peaks. A disadvantage is that it requires a large data base and a large amout of computational work to produce a single sumary.

Comparisons of the PSD curves from the different sources show similarities in the general shape of the curves. However, many variables influence both the magnitude and the exact frequency of the excitation. Some of these include suspension system, load, speed, road condition, condition of trailer (new, old), and location of cargo. The frequency peaks (0 to 5 Hz) are attributed to the natural frequencies of the suspension systems. These are influenced primarily by the suspension system and the load. Since these vary, it is expected that the peaks would be different for the same trailer with different loads, or for different trailers with the same load. The intermediate peaks are due to the unsprung mass and occur in the frequency range 10 to 20 hertz. The unsprung mass consists of the wheels, axles, and suspension system, and typically weighs on the order of 1,000 to 2,000 pounds. Assuming the sprung mass to weigh 20 times the unsprung weight, the unsprung natural frequency is on the order of four to five times greater than the sprung weight (based on the same spring rate). This frequency should be relatively fixed for a given suspension system regardless of cargo weight. However, this frequency will vary on trailers of different design.

The third high peak generally occurs in the 50- to 100-hertz range. This peak is apparently related to the tire natural frequency. Vibration tests on tires alone have recently been conducted and natural frequencies are reported to be in the 50- to 150-hertz range for automobile tires (43). The lower natural frequency is reported to apply to a radial tire and the higher frequency to a bras tire. Thus it would be expected that these would be in the same general range for truck tires. Tire resonance is excited by the vehicle when it travels at a forward speed that causes the tire print to impact the road in a critical time period. For automobile tires, these are reported to occur at a forward speed of 33 miles per hour for radial tires and 60 miles per hour for bias tires.

The remaining peaks and/or high vibration levels are due to structural elements vibrating at their natural frequencies. Schlue reports high vibration levels at high frequencies (over 100 Hz) caused by a suspension system in need of repair. Thus the frequencies of high and lwo energy will vary depending on the particular vehicle and load. Unless a specific vehicle and load combination is used, it is difficult to take advantage of the low energy inputs to the load. For general cargo, the vehicle and load are seldom known and energy inputs muse be based on all possible combinations of vehicles and loads. The imputs to road vehicles are principally from road roughness and are generally not characterized by periodic inputs except for pavement joints on concrete highways. As such, the vehicle receives random and impulsive inputs and tends to respond at the natural frequencies of various elements of the vehicle.

The previously described truck studies reporting data in terms of power spectral density are summarized in figure 6. As a result of the many variables, it can be seen that it would be difficult to characterize road vibration with a vibration spectrum having discrete peaks and notches. The studies, involving a number of vehicles, show peaks occurring at different frequencies covering a rather broad frequency range. These peaks, however, are approximately equal in magnitude and could easily be enveloped by a straight horizontal line (constant PSD). This procedure results in a conservative specification, since specific vehicles do exhibit peaks and notches in the spectrum. Probability levels can be assigned if it is assumed the probabilities presented by Schlue are valid. These show a 50-percent reduction in the peak PSD envelope occurs at the 95-percent probability level and an 80-percent reduction from the peak at the 50-percent probability of occurrence level.

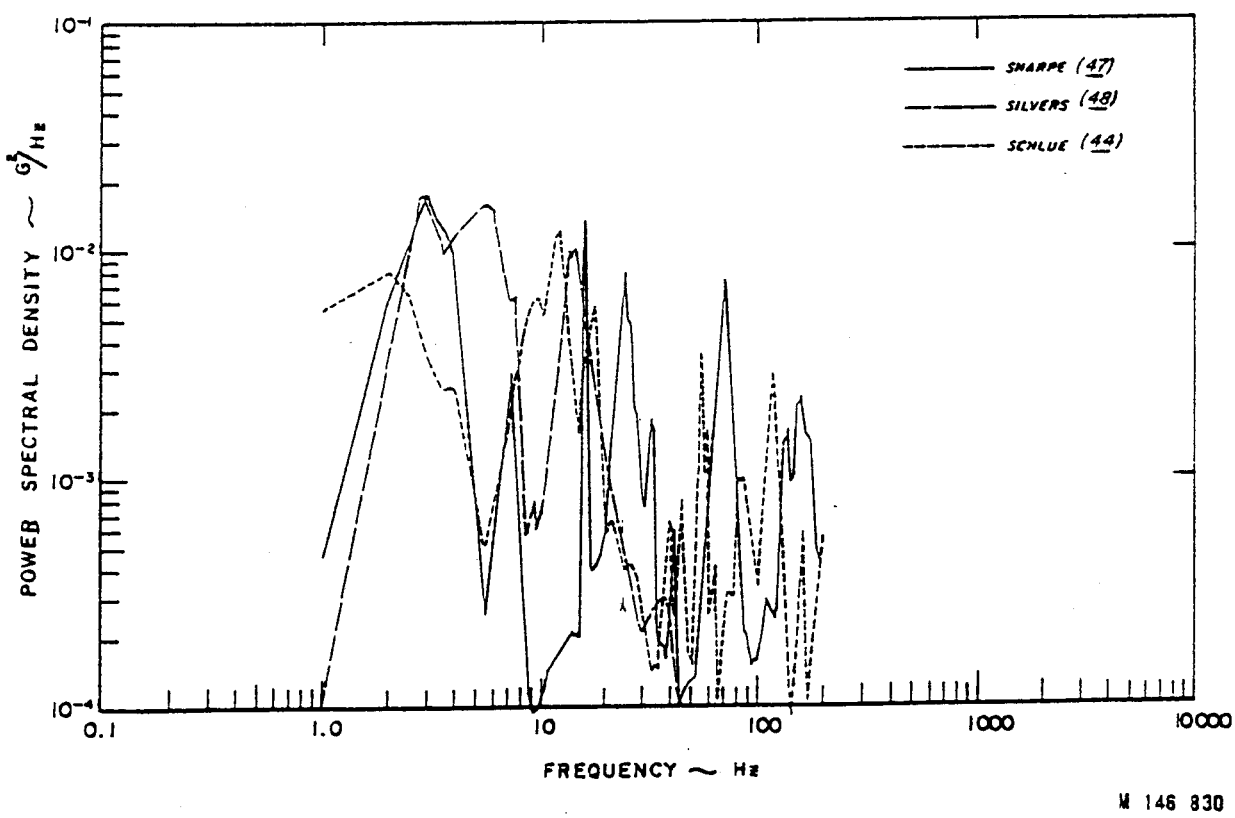

Figure 6. --Truck frequency spectra--summary of PSD data.

There are some minor differences in the reported results from the previously discussed programs. For example, there is disagreement as to the effect of load and the location (front *or* rear) of maximum vibration levels. The major difference in results occurs in the frequency range above 50 hertz. Higher levels are reported by two of the sources, but may be a result of poorly maintained or operating suspension systems.

Descriptions of vibration in terms of power spectral density are common and offer many advantages from an amlysis, design, and test viewpoint. For general cargo, they provide an indication of the energy levels in particular frequency bands, and therefore the potential for damage. However, for many package-related applications, i.e., design and test, descriptions in terms of acceleration and frequency are more usable.

Therefore the format selected. for a description of the truck vibration data is an envelope curve of peak acceleration versus frequency. An envelope curve, considered representative of most trucks, is shown in figure 7. The shape of the curve has been guided by the envelope of PSD data summarized in figure 6. The peak acceleration level was calculated

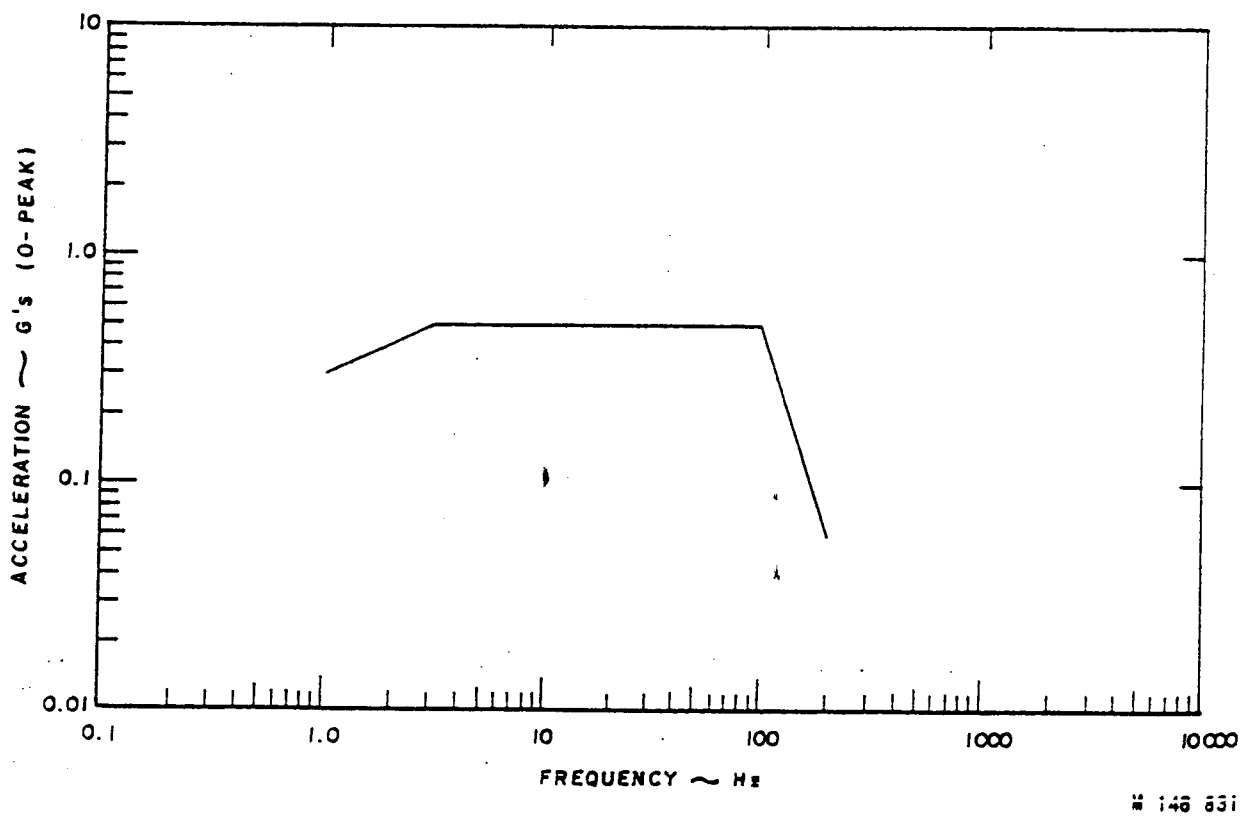

Figure 7. --Vibration envelope curve--truck summary.

from the PSD envelope (0.02 g^2/Hz). Assuming a 1-hertz bandwidth, $g_{rms} = \sqrt{0.02} = 0.15$. For a random signal, the Peak value is from 3 to 4 times the rms value, giving a value of 0.5 g. Thus, an envelope curve is drawn level from 2-1/2 hertz out to 100 hertz as indicated by the PSD summaries of figure 6. Acceleration values in this frequency range are reported near 0.5 g and are considered typical of most vehicles if the occasional high peaks, not considered representative of continuous vibration, are excluded.

The data base covering vibrations on trucks is extensive. The data cover a variety of truck and tractor-trailer combinations, loads, operating conditions, and suspension systems. Therefore, this hazard is considered well-defined. If detailed information is required concerning a specific load, vehicle, and operating condition, the information can be obtained from the individual reports listed in the bibliography. Most vibration studies have described the vibration environment in terms of cargo floor response, i.e., input to the cargo. The effect of the load on these measurements has been determined by monitoring the floor for different load conditions, i.e., no load, half load, and full load. The cargo, however, depending upon its characteristics (rigid, compliant), may significantly influence these measurements, particularly for loose cargo or cargo resonant conditions. (Alternately, the cargo, by reason of its compliance, may not respond to certain inputs.) Silvers resolves part of the problem for the light load condition by removing the cargo. He reports the lightly loaded vehicle exhibits the severest environment and describes the environment in terms of measurements on an empty vehicle. This technique is said to eliminate the influence of bouncing loose cargo on the recorded measurements.

Other studies have attempted to describe the truck vibration environment in terms of cargo response. Johnson (27) reports on measurements made on different sized packages carried on a 3-ton truck. Transients due to package bounce were separated from the background vibration and analyzed separately. A PSD envelope curve for the vibration data was developed and although the curve is based on measurements for severe road conditions, it has the same general shape as the envelope curve for cargo floor measurements shown in figure 6.

Correlation of cargo floor measurements with forces transmitted to the cargo has been attempted by Foley (13) via apparent weight measurements. The data show that although the truck floor is vibrated at a constant level, the force transmitted to the cargo drops off rapidly beyond 30 hertz. Force measurements were recorded at the cargo floor/cargo interface while floor accelerations were monitored in close proximity to the cargo. Additional work is required to correlate cargo floor measurements with cargo force inputs.

Railcar

Programs have been conducted for the sole purpose of characterizing the vibration environment for typical in-service boxcars. Programs have also been conducted to measure the vibration environment of trailers on flat cars (TOFC) and containers on flat cars (COFC). However, the same problems as those encountered in summarizing truck data arise in railcar data. These relate to the lack of consistency in data reporting and presentation. Data presentation still varies from peak acceleration and associated frequency, overall rms value of the composite signal, cumulative probability of accelerations for the composite signal, to power spectral density (PSD) plots.

Railcar vibration inputs differ from truck trailer inputs in that there are more periodic forcing frequencies associated with the rail system. Standard rails are 39 feet long and are staggered midlength from the left to the right rail. As a result, there is a periodic imput associated with the rail joints and the half-rail joints. In addition, there are periodic inputs to the car by the rail joints as a result of the car's geometry. These are associated with the overall axle wheelbase distance, the interior wheelbase distance, the truck center plate distance, and the truck axle/wheelbase. In addition, there is the periodic input of a wheel resulting from imbalance or a flat spot. As a result of the periodic driving or exciting frequencies, the railcar body responds at those frequencies. When any of the forcing frequencies coincide with a railcar system natural frequency, large responses occur, such as the low-speed rolling or rocking and wheel lift-off phenomenon. In most cases, the driving frequencies are below 20 hertz for train speeds up to 75 miles per hour. Welded track eliminates the periodic inputs associated with rail joints. This reduction has been demonstrated in a recent study, but the effect is not as dramatic as expected, since there is still the unevenness or roughness of the rail system. Railcar responses to rail irregularities on welded track are at system natural frequencies of car truck and track. Other vertical inputs to railcars are transients that occur in traversing intersecting tracks or road crossings. These impulsive loadings cause the railcar to vibrate at its natural frequencies.

As indicated, a number of programs have been conducted to determine the vibration environment on typical railcars. Various formats have been used to present the data, but in many cases, the data are reported in terms of PSD. In spite of this common format, correlation of data from different sources is still difficult because of the difference in the frequency ranges that are reported. Studies concerned with railcar truck performance have little interest in frequencies greater than 20 hertz. Another factor that makes comparisons difficult is the scale used to present the data. An order of magnitude reduction in vibration intensity merely shifts the data one scale cycle on a log plot. The

same data plotted on a linear scale show practically a zero value for an order of magnitude reduction.

Sharpe (46) reports on an investigation to determine the inservice vibration environment of a Hy-Cube, 70-foot, 100-ton boxcar. The test car was loaded with 30 tons of scrap iron to simulate a typical load. The only parameter varied in the test was the springing and damping of the suspension system. Data are reported for train speeds of 20, 30, and 45 miles per hour and for operation over both welded and jointed track. The data have been analyzed by a real-time wave analyzer having a resolution of 1/400 of the frequency range. The maximum PSD value reported was 8.2×10^{-4} g^2/Hz for a 0 to 500 hertz analysis and 3.8×10^{-4} g^2/Hz for a 0 to 200 hertz analysis and occurred at 60 hertz. Other predominant peaks occurred at 20, 40, 80, 120, and 400 hertz. These major peaks remained at the same frequencies even though the suspension was altered and the speed varied. This would seem to indicate that these responses are more a function of car body natural frequencies which are excited by impulsive loadings at the wheel-rail interface. Other observations were that: (1) increased speed resulted in increased levels of vibration, (2) vibrations on welded track were lower than those on jointed track, (3) the intermediate and hard spring system reduced the middle frequency peaks (50 to 150 Hz) and increased the high frequency peak (400 Hz), and (4) the softer spring system shifted the 400-hertz peak to 315 hertz and reduced the low frequency (less than 20 Hz) peaks. Operations on welded track essentially eliminated all the peaks. The PSD data for welded track have the appearance of wide band random vibration. It was reported that data records were not long enough to provide accurate PSD analysis of the low frequency input. However, a spectral analysis of a 20-second segment of data was performed. The analysis showed few predominant frequency components and acceleration levels less than 0.05 g. The predominant peak (3.4 Hz) occurred at the half-rail joint frequency on jointed track. This peak did not show up in any of the data recorded on welded track.

Guins reports on data from two separate studies. The first[3/] is a reevaluation of Luebke's data (31), and the second is a preliminary report of an AAR 5,000-mile boxcar test (22). Luebke's data apply to an artificially disturbed track (horizontal and vertical) and are therefore not considered applicable to normal track conditions. However, some of the observations and conclusions do apply. Conclusions from the reevaluation with regard to car body vibrations are: (1) the predominant frequencies are those of half-rail joint input, (2) accelerations at higher speeds reach a maximum of 50 miles per hour and thereafter main-

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3/ Guins, S. G.: Effect of Vertical Track Irregularities on Car Body Vertical Accelerations, Personal Communication.

tain that level, and (3) softer car suspension springs reduce acceleration levels, but not dramatically. A high frequency peak reported by Luebke was not evident in the analysis of the base car data. The base car, as the name implies, is a base of reference. Since data from the base car did not show the characteristic high frequency peak reported for the test car, it was concluded that this response was probably due to the method of mounting the transducer on the test car.

The other program reported by Guins (22) is an AAR test program. The study covered 5,000 miles of typical revenue service for a 60-foot, 70-ton boxcar equipped with a sliding-sill cushioned underframe. The car was loaded to approximately 3/4 capacity (98,640 lb) with concrete blocks. Concrete blocks were used because they could be securely braced and would provide a nonenergy absorbing lading that remains the same throughout the test. The data recorded in this test program are still being analyzed. However, preliminary analysis shows very little response above 15 hertz. Most of the significant peaks were below 10 hertz. Further analysis of these data is being conducted and should provide further definition of the rail vibration environment.

Foley (16) summarizes Sandia data from three rail trips as well as other publish; data. Data for the three trips were reported previously (18) and are shown in graph form in figure 8. The data cover measurements recorded on a rail flat car and summarize 22 different events. The test car was part of three different train lengths, varying in size from 65 to 120 cars. Foley summarizes the data in the form of rms acceleration level versus frequency covering a frequency range of 10 to 350, hertz. Frequencies below 10 hertz are described as being dominated by recurrent transient impulses and are described in terms of shock spectra. A report by Foley (14) summarized the rail data on the basis of a 99-percent probability level and included data down to 1 hertz.

A study reported by Byrne (9) was primarily concerned with evaluating freight-car trucks, while car body vibrations were of secondary importance. Tests were conducted with a 70-ton refrigerated boxcar in both the empty and fully loaded conditions. Truck and car body responses were monitored during operation on welded and jointed track and for both tangent and curved track. Wheels having cylindrical wheel treads as opposed to standard tapered wheel treads were used in an effort to eliminate the vertical responses resulting from truck lateral instabilities. Standard tapered wheel treads serve to keep the trucks centered between the rails, while the wheel flanges serve to limit the lateral excursion of the trucks. However, at certain speeds, there are lateral instabilities related to truck “hunting”. Initial testing with the test car showed the threshold of hunting occurred between 40 and 50 miles per hour on half-staggered jointed-rail track, and above 50 miles per hour for operation on continuous welded track. The major peaks on the PSD slots of vertical vibration are shown to be related to the rail joint frequency, while others are related to the truck center geometry. All

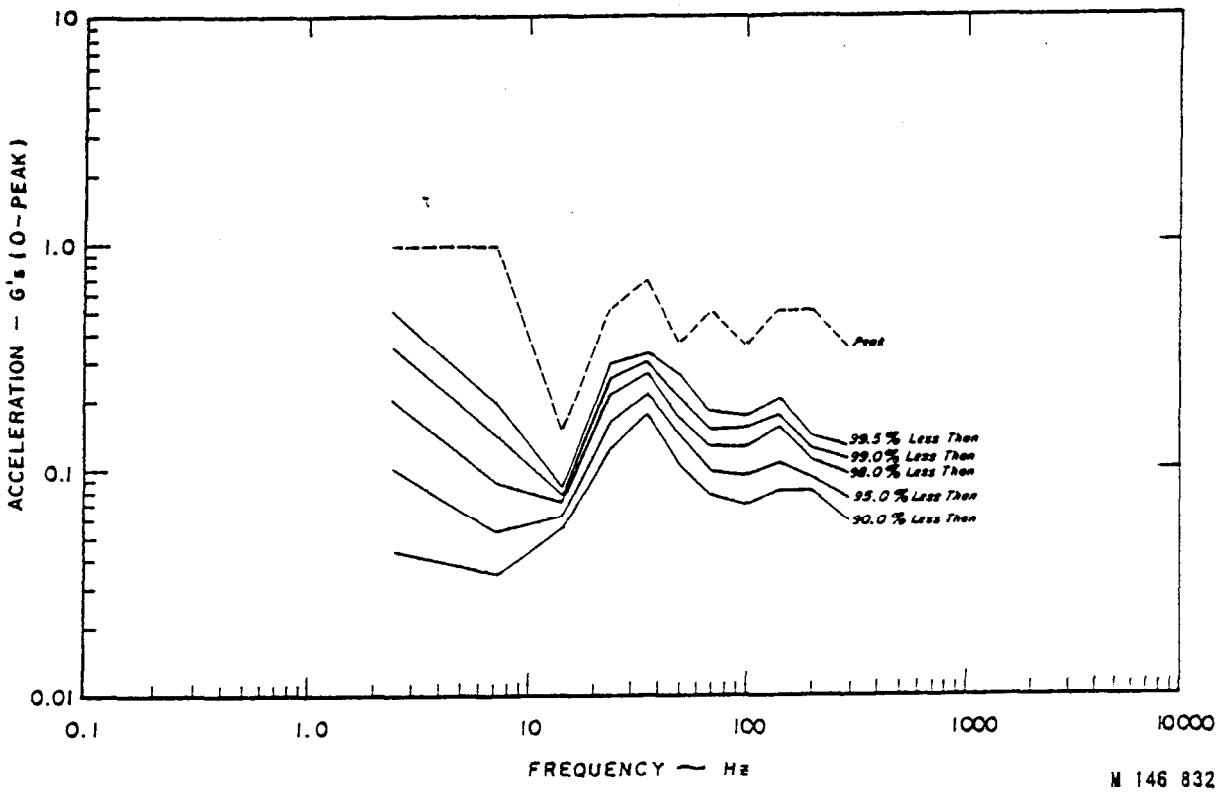


Figure 8. --Frequency spectra for various probabilities--railroad (vertical direction, composite of various conditions).

of these are below 6 hertz. Some of the peaks remained constant regardless of car speed and appear to be related to car-body and truck structure-system response. PSD analyses were performed up to 20 hertz.

A recent investigation of container flat car ride quality is reported by the Trailer Train Company and Freightmaster (21). Tests were perfomed with an 89-foot flat car with 20- and 40-foot containers. Ride quality is reported in terms of a fixed probability of occurrence of acceleration level. The raw data were first filtered with a low-pass filter having a 15-hertz cutoff frequency. Cumulative probability curves. of acceleration were then plotted and the 95 percentile chosen to summarize the data. The data were reported to show the following characteristics. There is a sharp rise in the general level of accelerations throughout the system at about 50 miles per hour and this appears to be associated with truck hunting. The amount of lading has a pronounced effect on ride quality, but the rigidity of the lading had no clear pattern. Container length had no major effect. The vertical vibrations were more severe on the end overhang and less severe near the center of the car. Wheel wear (i.e., worn wheels) significantly increased the level of vibration.

A summary of railcar vibration data reported in. terms of PSD is shown in figure 9. The data are from three independent studies. Byrne's (9) data cover the low frequency range, while Foley's (16) and Shapre's (46) data cover the intermediate and high frequency ranges. Foley's data were reported as an envelope curve and, therefore appear as straight lines in the summary plot. The other data are plotted in terms of the highest reported levels. The datacover a wide frequency range, but there is not much overlap between the data sources to give confidence to the results. However, the data do show a relatively constant PSD level over the reported frequency range and this correlates with Foley's acceleration data presented in figure 8. The data in figure 9 show an order of magnitude reduction in PSD level for railcars when compared to the truck summary of figure 6.

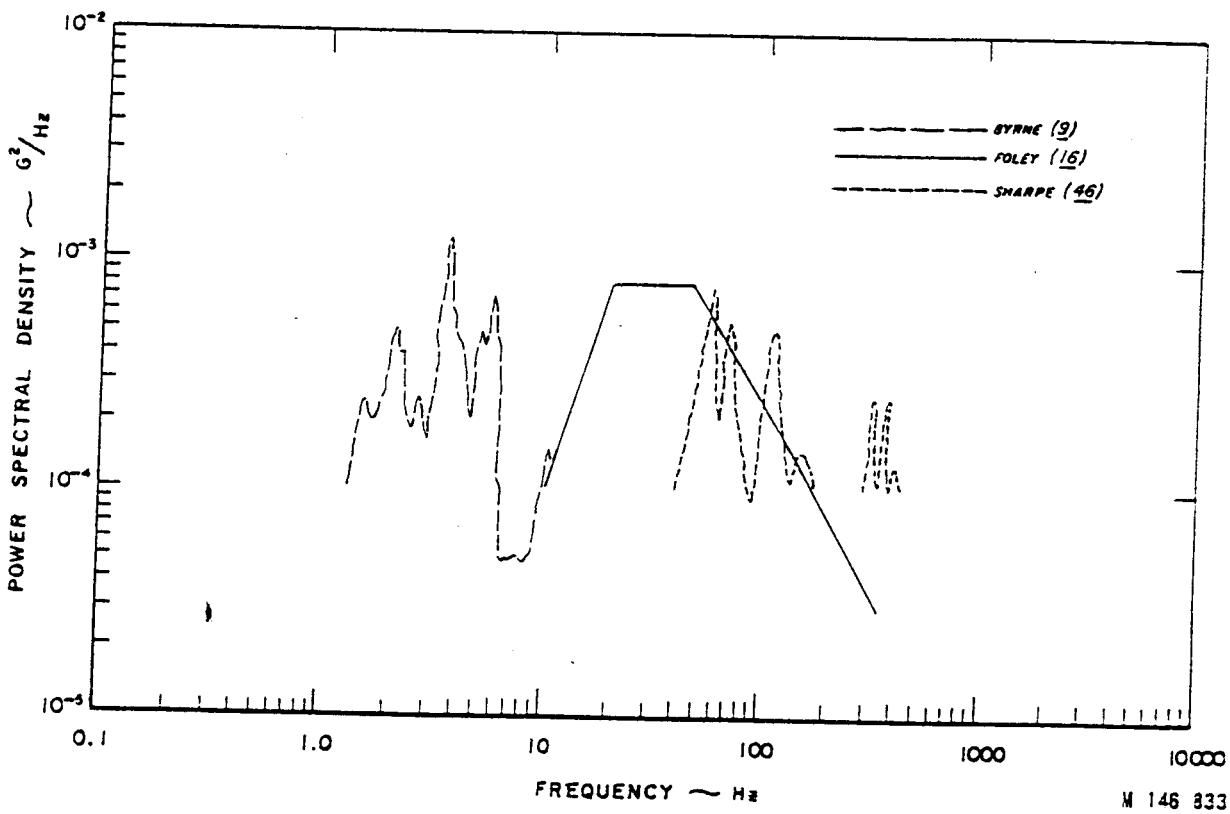


Figure 9. --Railcar frequency spectra--summary of PSD data.

The railcar vibration environment has not been studied as extensively as trucks. This situation may be due to the reduced severity of vibration relative to trucks as noted previously, or the inability to conveniently conduct a railcar measurement program.

Based on the results of the studies conducted to obtain data, the predominant frequencies in railcars can be established. However, there is a considerable variation in the magnitude of the acceleration levels reported. Foley reports that data below 10 hertz show no relation to vibration-like distributions, and that this is the frequency range in which the highest amplitudes are found. Further work in this area is required to better characterize the environment in this frequency range as well as defining the vibration levels more accurately at all frequencies. The AAR test program, which remains to be completed, may provide the information needed to fill in these gaps. Nevertheless, an interim description can be developed based on available data. Assuming the data of figure 9 are valid, an envelope curve corresponding to a constant PSD level of 10^{-3} g^2/Hz can be drawn. Following the guidelines used in developing the truck envelope curve, the railcar envelope curve shown in figure 10 is developed. Although this curve is based on rather sparse data, it compares favorably with a previous statistical summary shown in figure 8.

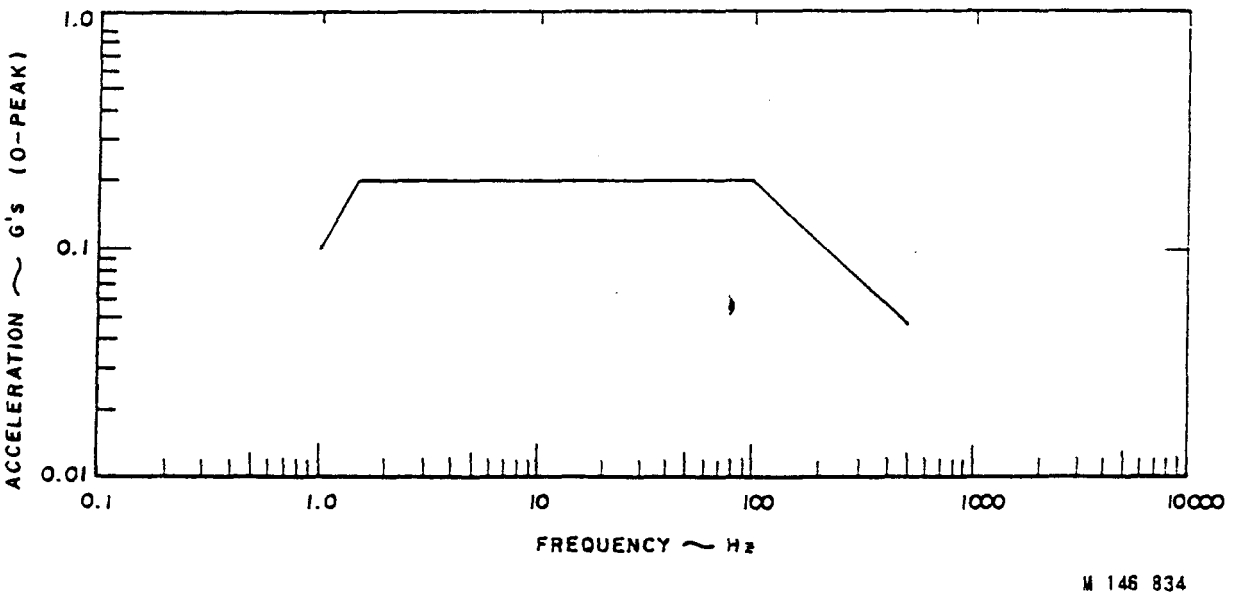


Figure 10. --Vibration acceleration envelope--railcar.

Aircraft

The vibration environment on cargo aircraft can be broadly classified as due to internal or external sources. The excitation frequencies are highly dependent on the type of aircraft (turbojet, turboprop, reciprocating engine, or helicopter) while the amplitudes depend more on the flight mode (takeoff, climb, cruise, and landing). For a particular aircraft, many of the acceleration peaks can usually be associated with internal sources. They are due to periodic excitations from the rotating engine, propeller blades, turbine and/or other rotating shafts. In addition, there are the other external random excitations such as air turbulence, air gusts, and runway roughness (during landings).

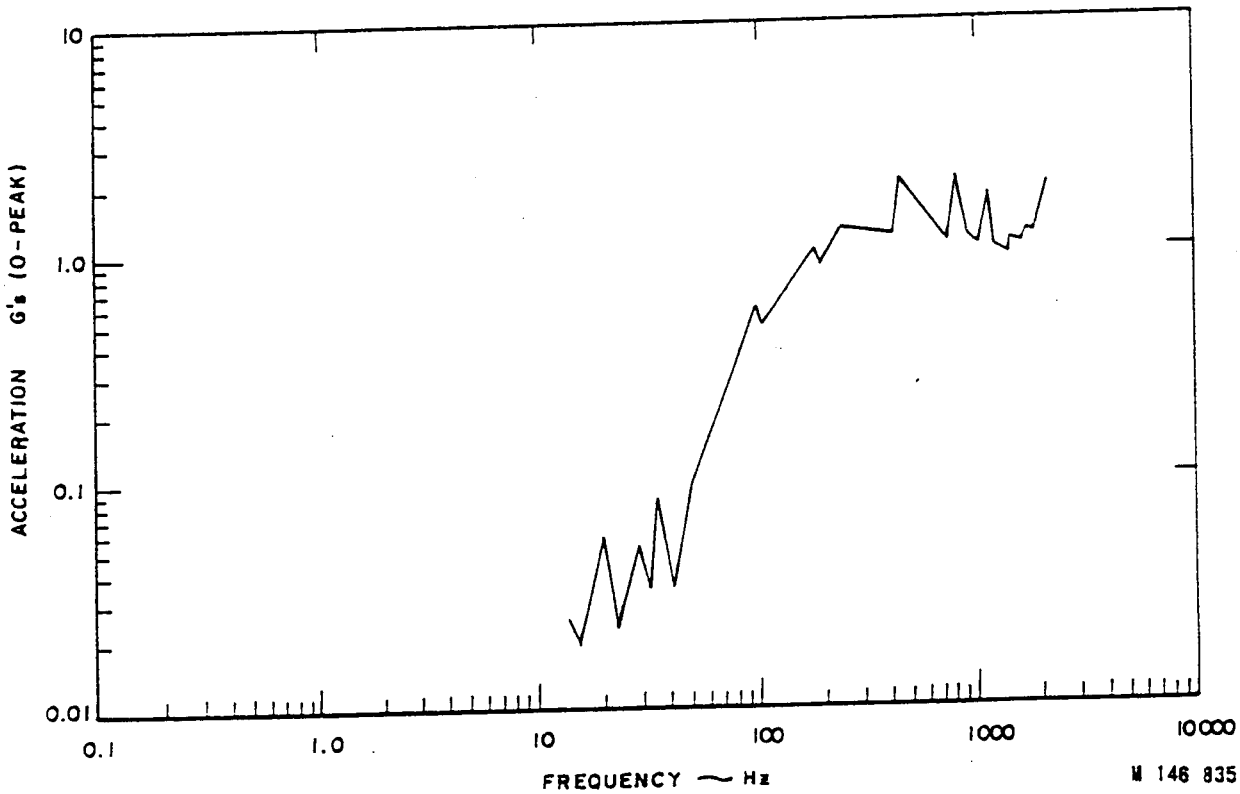
Available data describing the aircraft environment have been summarized (37). Data are presented for turbojet, turboprop, reciprocating engine and helicopter aircraft. A recent review is reported by Foley (16) and includes data recorded on a number of C-5A and C-141 cargo aircraft. The other data are reported in detail (32). The data are summarized with respect to type of aircraft (turboprop, turbojet, and helicopter) and for two events (takeoff and climb mode, and cruise mode). Takeoff and climb modes are descriptive of short-term high amplitude levels, while cruise modes are typical of long-term, low-level amplitudes. The data are reported in terns of rms acceleration levels versus frequency and are described as continuous broadband vibration. Single frequency excitation components are identified separately on the curves. Similar data are presented for turboprop aircraft. Summary curves for helicopters are also reported.

Descriptions of the aircraft vibration environment are complete for most of the commonly used turbojet cargo type aircraft, i.e., 707, C-5A, and C-141. Although aircraft with reciprocating engines and helicopters are used occasionally, they are not considered to be in common use and therefore have not been discussed or reviewed for this study. The turboprop aircraft environment is different from the turbojet aircraft in that it has a characteristic single-frequency, high-amplitude excitation. In other modes of transportation, discrete excitations also were present, but they varied in frequency due to variations in vehicle speed and roadbed conditions. For a given turboprop aircraft, the engine normally operates at a relatively narrow speed range with the propellers producing a sinusoidal-type input. For the C-130 aircraft, this excitation frequency occurs at 68 hertz and at 48 hertz for the C-133. These frequencies therefore will be fixed relative to the other excitations which will vary in frequency and magnitude.

The data presented by Foley (16) are in general agreement with data presented (37), if a conservative assumption is made regarding the relationship between rms values and peak values (i.e., peak value is

equal to 3 x rms). An envelope curve of turbojet data is shown in figure 11 (35). The data apply to military version of the Boeing 707 and include data from various locations on the aircraft during ground runup, taxi, takeoff, and cruise conditons. Statistical data for another version of the 707 turbojet are shown in figure 12. Good correlation is evident between these independent studies throughout the frequency range investigated.

A summary curve, enveloping data considered typical of common carrier cargo aircraft, is shown in figure 13. The curve includes data from turbojet aircraft only since other type aircraft are being phased out. It is apparent that the damage potential to cargo for aircraft is lower than truck or railcar.



Figuue 11. --Aircraft acceleration envelope--turbojet composite.

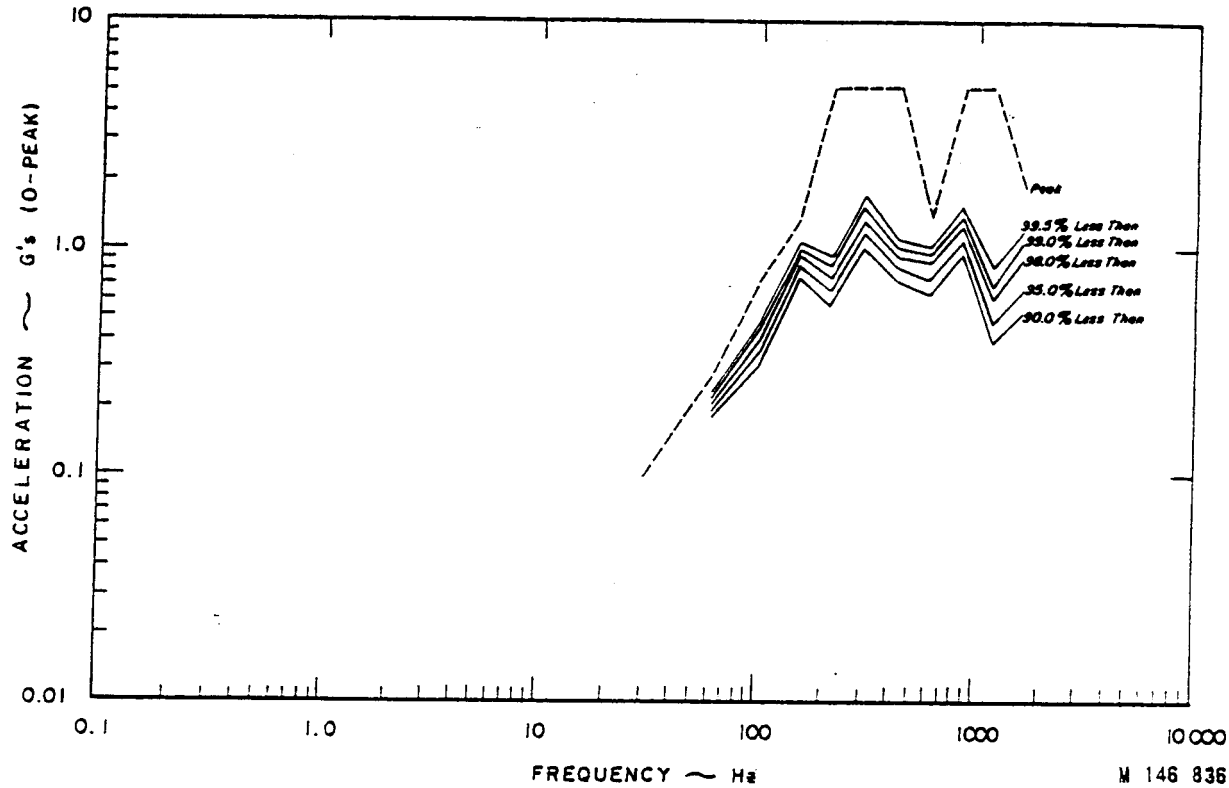


Figure 12. --Frequency spectra for various probabilities--turbojet aircraft (vertical direction, takeoff).

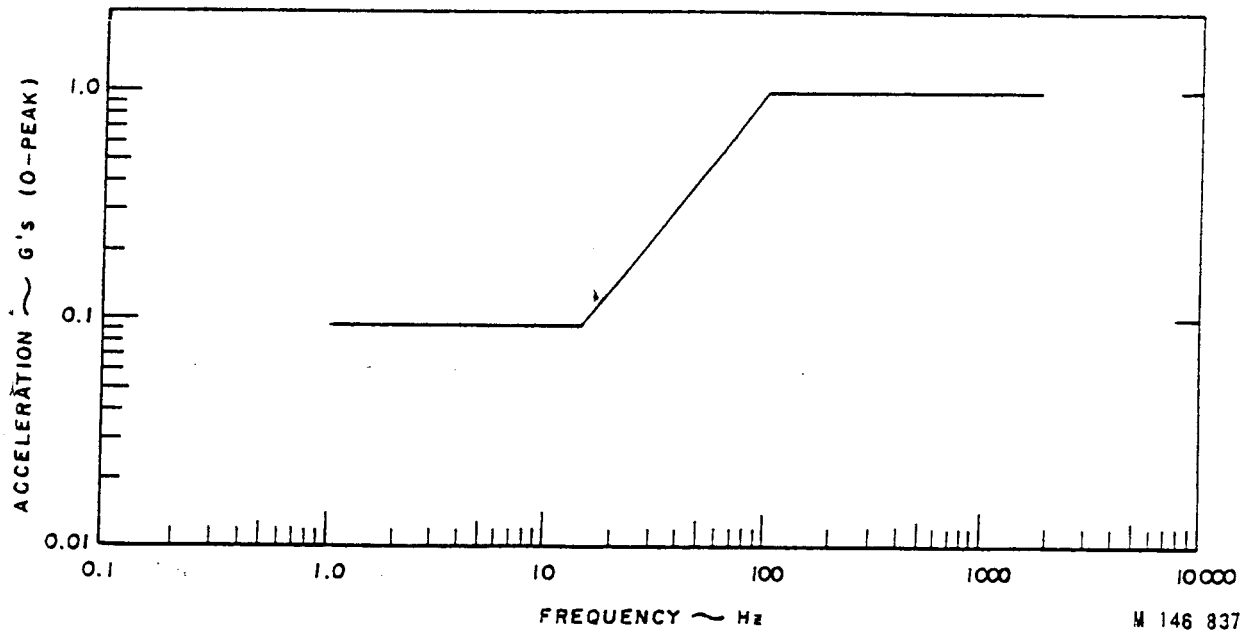


Figure 13. -- Accelerating envelope--aircrat.

Ships

The vibration environment on commercial cargo ships is not well defined. Most of the ship measurement programs that have been conducted have been concerned with Navy vessels. This lack of data may be caused by several factors including a belief that the ship environment does not represent a severe vibration hazard when compared to other transport modes or the extensive program required to compile ship vibration data. The data presented (35 , 37) are still the most current, based on available data.

The available data on ships indicate two distinct levels of vibration which are dependent on sea condition: low-level continuous type vibrations are characteristic of ships operating in calm water and are a result of engine and propeller excitations. Higher levels of vibration are characteristic of rough seas and are a result of: the ship riding up and down on the waves or swells; the waves impacting or pounding against the ship; and the ship slamming against the water (caused by the ship's bow rising out of the water and then falling back into the water with a slam).

The wave-induced motions resulting from the ship riding up and down on waves have been reported for a 520-foot dry cargo ship. The data are summarized in figure 14, showing the probability of occurrence versus acceleration level. These wave-induced vibrations are reported to range in frequency from 0.03 to 0.20 hertz. Since they are at such low frequencies, they can be considered more seismic in nature. Thus their effect on cargo would not be typical of vibration, but more of a quasi-static compressive loading. The other extreme values were reported as being due to whipping, which produced ship response at 1.5 hertz, and slamming, which produced ship response in the range of 5 to 20 hertz.

Another major area of concern for cargo transported by ship, particularly for containers on the decks of ships, is the quasi-static type load resulting from very slow, but large amplitude rolling and pitching motions. A discussion of the loads imposed on containers and their restraints as a result of these motions is presented in (24). An extreme case produced a maximum lateral or across-the-deck load 0.08 g (calculated for a 40° roll angle). Because of the slow oscillations, these motions are also considered more in terms of static compressive loads than vibration type loads.

Foley (16) summarizes ship data in terms of rms acceleration level versus fequency for continuous type vibration. The summary shows very low levels of vibration, less than 0.03 g from 10 to 200 hertz and less than 0.01 g from 200 to almost 2,000 hertz. The summary is reported to include data from a number of sources. It is apparent that many of the high-amplitude transients have not been included in this description.

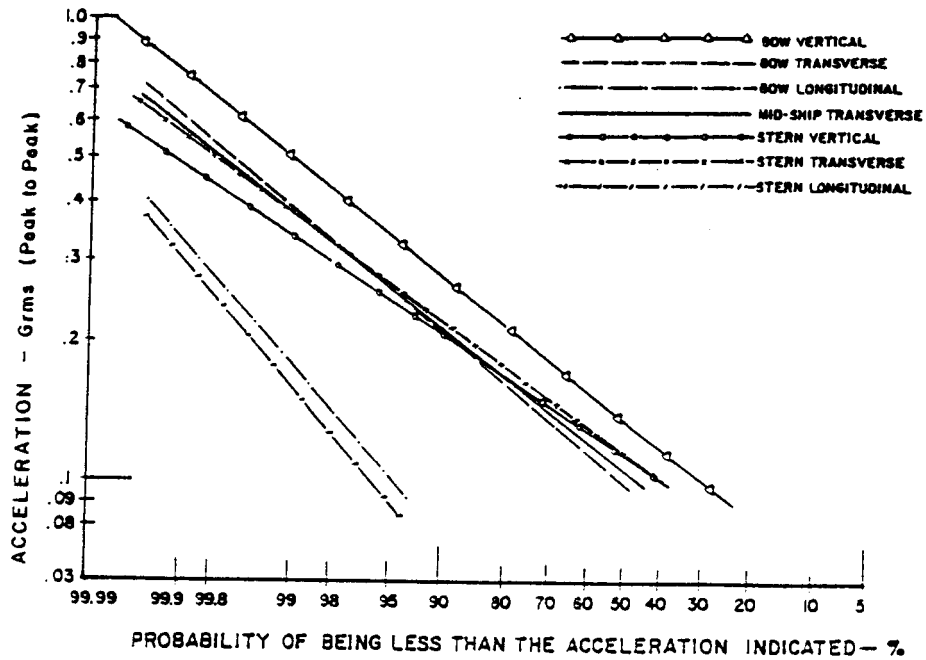


Figure 14. --Wave-induced acceleration versus probability of occurrence (520-ft. cargo ship).

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Based on a review of the preceding sources, a representative summary curve has been developed. The envelope curve in figure 15 does not include the very low frequency (less than 1 Hz) nor the high frequency slamming excitations. These exclusions are considered justified in view of the fact that cargo would not be sensitive to very slow oscillations, from a vibration viewpoint, and slamming can usaually be avoided.

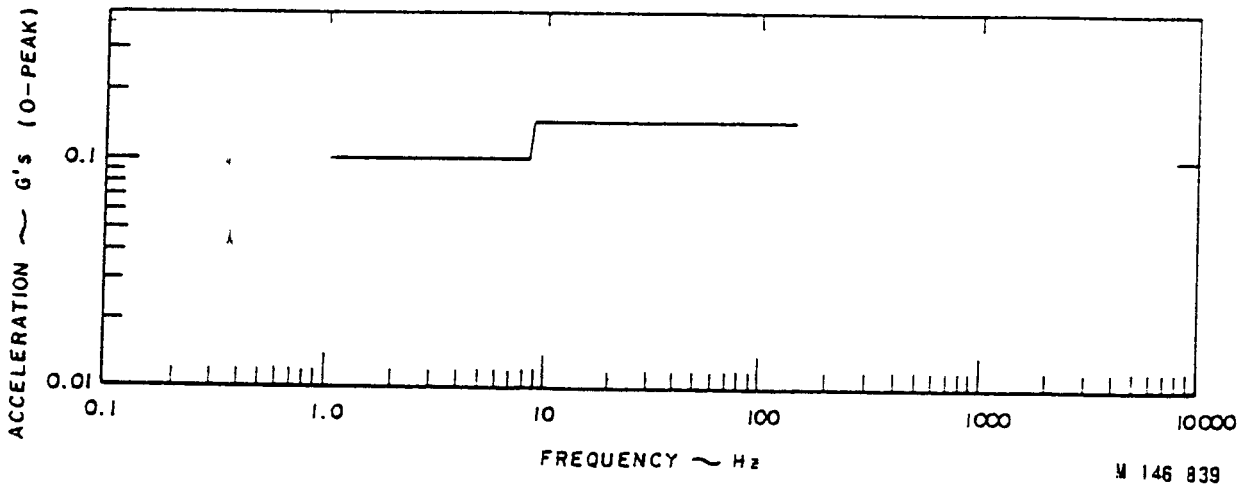

Figure 15. --Vibration spectrum envelope--ship.

Assessment of Vibration Data

Many studies have been conducted to determine the vibration environment on common carrier vehicles. However, the data have not been analyzed nor reported in a consistent format. Nevertheless, much of the data can be compared and, when it is, there is reasonable correlation. Some differences are reported in the data, but they are not considered significant. The trend in recent studies has been to analyze and report vibration data in terms of PSD. Power Spectral Density data reduction procedures and systems are readily available, automated, and capable of reducing large quantities of data in a short time. For package-related problems, however, peak acceleration versus frequency is considered more useful based on existing test equipment and package design procedures. Available PSD data, therefore, were processed for presentation in this format. This processing involved making an assumption regarding the distribution of peaks, but the results showed good correlation with previously reported data.

The vibration environment is very complex, being composed of many frequencies whose amplitude varies with time. Therefore, a description in terms of a peak acceleration versus frequency must be viewed and used with caution. A direct relationship has not been established between the effects on cargo of a constant amplitude sinusoidal vibration and random vibration. The vibration descriptions developed do not include the extreme values reported in previous studies. These peaks have been shown to occur infrequently and at levels significantly above what is considered representative of continuous vibration.

The data presented are representative of the maximum vibration levels. Previous studies have shown the effect of direction, load, location, speed, and other factors. For general cargo which can be located at any position and in any orientation, the maximum levels are considered adequate for vibration descriptions.

Presentation of data in a common format permits a comparison of the various modes. It shows, for example, that trucks impose the severest vibration loads on cargo with the railcar next, followed by ship and aircraft. The jet aircraft shows high vibration levels at high frequencies, but these are not considered damaging to general cargo.

Many transportation vehicles and systems remain to be defined. These include the container on flat cars (COFC), trailer on flat car (TOFC), commercial cargo ships and specific turbojet aircraft. However, the environment appears to have been described for the severest condition, i.e., truck transport which is present in almost every distribution cycle.

SHOCK

The shock environment presents a particularly difficult parameter to characterize because in most cases it must first be separated from vibration type data and then analyzed separately. What may constitute a shock or transient to one investigator may not be so defined by another. As an example, a transient pulse due to a road pothole may be considered a shock pulse in one case and a vibration type input in another. This may be more a result of being able to isolate or separate the data. In other cases, e.g., crossing a railroad track, or railcar impact, the transient is clearly evident and so identified. As was true with vibration studies, shock data have been reported in a variety of forms. In addition, the data have been recorded either on the cargo itself or on the cargo floor. When the data have been recorded on the cargo, the data have generally been reported in terms of peak acceleration. When the data have been recorded on the cargo floor, the data have been reported in terms of peak acceleration, shock spectrum, or spectral analysis. Depending on the end use of the data, each form of data presentation has its advantages and disadvantages.

Peak cargo acceleration has many advantages in that it can be related to product fragility or "g" rating. It is a factor often applied by packaging engineers in design to ensure safe transportation of cargo. This approach requires that a maximum dynamic acceleration level or "g" level cannot be exceeded by the cargo. In many studies, however, only the peak input acceleration for a given shock event or element in the distribution cycle is reported. This format is not particularly useful for design purposes unless the product is simple and unprotected. More sophisticated studies have translated the shock input to shock spectra or peak acceleration response versus system natural frequency. With this format, the packaging engineer can determine the maximum value of response at dominant frequencies due to the input motion at the points where cargo is located. A variation of the shock spectra is a wave analysis which presents the peak acceleration input as a function of frequency. Based on data presented in this format, one investigator concludes that most of the over-the-road transients could be simulated with a random vibration generator. A more detailed discussion of shock-data reduction procedures is given in (23).

In most studies, the shock input to cargo as a result of various transient events encountered during transport are separated from the continuous type inputs for more detailed study. In general, these transients are identified from the reams of data by means of a voice charnel or marker, and/or a visual review of the data records. The transient inputs result from discrete inputs to the transporter. For railcars, vertical transients occur when the cars cross intersecting track, switches, roadways, or bridges. Longitudinal inputs occur during

switching or coupling operations and during run-ins and runouts. Vertical transients to trucks occur when they traverse potholes, tracks, bridges, bumps, or dips. Longitudinal shock input occurs when the truck backs into a loading dock. Transient inputs to aircraft occur during a landing impact and in rough air turbulence or gusts.

Trucks

Schlue (44) has analyzed the transient data recorded during trans-continental shipment of spacecraft via air ride suspension vans. The data are presented in terms of shock spectra calculated with an assumed amplification factor of 10. The spectrum represents the response of a series of single degree of freedom oscillators, each having a fraction of critical damping of 0.05 ($c/c_c = 0.05$). This factor corresponds to typical structural damping for bolted and riveted connections. Typical shock spectra plots are summarized to show the maximum, 95- and 50-percentile levels of data samples from 21 events recorded at the rear locations (on the truck floor).

Similarly, Foley has reported truck shock environment in terms of shock spectra for a number of vehicles and for a number of events. The events included trucks traversing bumps, dips, potholes, railroad tracks, and backing into loading docks. The data have previously been reviewed and reported (37) and are available in greater detail in other referenced sources. Foley (16) has recently summarized these events in terms of envelopes of shock spectra. Composite curves are presented which envelop the shock response for the three directions (vertical, transverse, and longitudinal).

Kusza and Sharpe (47) have analyzed transient data recorded on typical commercial trucks in terms of peak acceleration versus frequency. The study covers several truck trailers loaded to different capacities (weights). Caomparisions were made between a curve computed for a transient event (truck entering a bridge at 60 mph) and a curve for conditions just prior to the event. It is reported that the general shape of the curves were the same, but much higher acceleration levels were present during the transient. Other transient data are reported in terms of peak acceleration of the composite signal. Peak values of 2.7 and 5.0 g are reported for a truck striking a prominent joint in the highway and a road intersection, respectively. One conclusion from this study was that transients produce increased low-frequency vibration and not sharp pulses. It is further concluded that if a random noise generator is used to generate a test signal, these higher levels will be produced automatically.

A much different form of presentation is the shock data reported in a European study (27). In this study, acceleration measurements were made directly on a number of packages. These packages were carried on a commercial 3-ton truck which was driven over a variety of terrains. Seven package types varying in weight from 50 to 2,200 pounds were used. Accelerometers were attached to the outside of these packages and recorded response in all three axes. Transients due to package bouncing were separated from the continuous vibration data and the two types of data analyzed separately. It was reported that terrain, truck speed, gross load, and package position had the greatest effect on acceleration levels. Unfortunately, much of the reported data apply to operations on very rough roads, including cross-country terrain and a potholed test course. It is reported that for a lightly loaded truck, once the package started bouncing, there was a small difference in the peak accelerations and distribution for five different truck speeds. This effect was studied for speeds between 8 and 15 miles per hour and showed pulses varying from 5 to 35 g. The majority of the peaks were between 5 and 15 g.

Peak acceleration distributions, i.e., peak acceleration versus number of occurrences, changed when there was a large change in speed. This effect was studied by segregating the data in speed ranges from 0 to 15 miles per hour and 15 to 27 miles per hour. The higher speed regime produced higher peaks and a greater number. The effect of position of the cargo on the vehicle for the lightly loaded condition was also studied and showed the aft or rearward position experienced much higher acceleration levels. The effect of cargo load on peak acceleration levels showed the heavily loaded vehicle experienced much lower levels of acceleration. For the package weights investigated, there appeared to be only a small effect of the package weight on the acceleration levels. Heavier packages showed lower acceleration levels. All the pulse shapes were reported to be nearly half-sinusoidal with a pulse duration of 3 to 5 milliseconds for better than 90 percent of all values recorded.

A unique approach to measuring the truck transportation shock environment has been reported in a British study (30). In that study, glass bottles, electric bulbs, and glass ampules were used in lieu of instruments because of their low cost and low fragility rating. The number of items broken in a given shipment was used to give an indication of the intensity of the environment. The advantage of this approach is reported to be the obvious low instrumentation costs and the ease of assessing damage. A visual picture of the damaged glassware is also immediately obtained, while the numbers and location can be easily recorded and interpreted as opposed to electronic recordings, including gravity, frequency of occurrence, plus shape and duration. In order to quantify the recorded breakage, experiments were conducted to correlate breakage with drop height and velocity change. The results showed that for the

location of maximum damage (the rear overhang), glass breakage corresponded to equivalent drop heights of 6 inches or less.

Rail

The shock environment on a flatbed railcar has been summarized by Foley (15) in terms of shock spectra. Shock data were recorded during transportation of a nuclear waste cask over a route that covered approximately 500 miles and involved several trains varying in length from 65 to 120 cars. The data are summarized to show shock spectra for a normal coupling operation (2- to 5-mph coupling) and during the crossing of an intersecting track (laid 90° to those on which the car was running) at 45 miles per hour. Another summary (16) presents shock spectra envelopes for a number of representative transient events. The curves are shown for the three vehicle axes, i.e., vertical, lateral, and longitudinal. Additional shock spectra for particular events such as slack runouts, run-ins, and track crossings are also available (37).

Sharpe (46) reports transient input to cargo in terms of peak acceleration of the composite signal. The peaks were read from data which was first filtered to 200 hertz. Peak accelerations varied from 1.4 to 0.95 g and were reported due to rail crossings. Two distinct types of response are reported. In one, the data showed a uniform increase and subsequent decline with time. The other showed a large initial acceleration followed by a slow return to pre-transient conditions.

Aircraft

Cook (10 , 11) reports on data recorded on the cargo deck of the C-5A and C-141 aircraft during normal transport operations. The data are presented in the form of acceleration response. Only data in the low-frequency range (0 to 30 Hz) were analyzed. Several loading conditions were investigated involving a number of takeoffs and landings and extended flights. It is reported that the two worst conditions occurred while flying in turbulent air and during a landing impact. The aft location experienced the severest vertical loading.

Maximum envelopes of the vertical acceleration response spectrum calculated from the acceleration time histories for both landing and impact, and turbulence for each of six transducers positioned at the forward, center and rear locations of the cargo deck are reported for the C-141 and C-5A aircraft.

Ships

The only significant shock loading to cargo onboard ship occurs when the bow of the ship leaves the water and returns with a slam. Data recorded on several ships during a slam event are reported in (37). For most cargo ships, the bow area receives the highest input. Case histories of reported cargo container damage are documented (24), and although one case indicated a slam event, the analysis showed slamming was unlikely.

Forklift Truck

The shock environment on four industrial-type lift trucks is reported by Gens (19). The study included lift trucks with capacities of 2,000, 3,000, 4,000, and 7,000 pounds; trucks with pneumatic and solid tires; and trucks powered by gasoline engines and electric motors.

The data are summarized in terms of envelopes of shock spectra. It is reported that there is an absence of any significant continuous broad-band excitation regardless of the type of motive power. Some of the pulses had peaks as high as 0.7 g in frequency bands below 15 hertz, while peaks rarely exceeded 0.1 g at higher frequencies. Of the variables investigated, the one that had the greatest influence with respect to producing a smooth ride was the ratio of capacity of vehicle to the weight of the load. The truck most heavily loaded had the smoothest ride. The type of tire had little, if any, effect.

Assessment of Shock Data

A review of available shock data with reference to general cargo or package-related problems indicates these transients to be of relatively low level except for railcar coupling. Further, it is apparent that the shock inputs or transients have been included in some of the vibration descriptions. Current shock descriptions in terms of shock spectra are of most value if applied to cargo firmly attached to the cargo floor. This is generally not the case for general cargo which is free to move. Finally, the transients, even for the severest road condition, impose loads which are equivalent to drop heights of less than 6 inches as evidenced by the glass breakage studies (30). Packages instrumented to record drop height are reported to be insensitive to transport shocks even when calibrated to record 3-inch equivalent drops.

Although the shock environment on vehicles is low when compared to other hazards, there still exists the phenomenon of package bounce or

repctitive shock which can be very damaging. There is a definite need to characterize the shock environment in terms which are applicable to general cargo. The descriptions of cargo response as reported (27) may have application in this area. These descriptions, which are given in terms of cargo accelerations versus number of occurrences, would be useful if they could be simulated in the laboratory. These shock effects, however, may be adequately covered by current vibration descriptions of empty vehicles. Currently, there is no correlation between the vibrations recorded on an empty vehicle and the corresponding shocks recorded on a bouncing package. Further study is required in this area.

RAILCAR COUPLING

Railcar coupling shocks are considered separate from other transport shocks because they can impose severe loads on cargo. These coupling shocks are a result of impacts between cars during train makeup in switching yards. The loads are predominantly longitudinal, i.e., along the longitudinal axis of the car, although significant loadings can occur in the other directions. The magnitude of the shock loading is influenced by such factors as: (1) impact speed, (2) weight of cars, (3) coupler design, (4) load configuration (integral and rigid, non-integral such as cartons, compartmentalized, slack, etc.), (5) number of cars active in impact, (6) location of test car, (7) track orientation, (8) car center of gravity location, and (9) length of car. Many of these factors have been investigated under controlled test conditions.

Impact Speed

Independent studies have been conducted to monitor the various impact speeds that occur during makeup of trains in marshalling yards. In a typical operation, the cars roll down a track under the influence of gravity and impact with a standing string of cars. The impact speed is a function of operating personnel skill and performance. A minimal impact speed of approximately 2 miles per hour is generally required for actuation of the automatic couplers, while 4 miles per hour is considered undesirable because of potential damage to cargo. Since human judgment is required, however, a wide range of impact speeds can bccur. Typical impact speeds from several surveys are reported by Ostrem et al. (35). The most recent survey reported (51) is based on 4,647 observations (fig. 16). The data show 99 percent of the observed impacts were below 10 miles per hour, while 50 percent were above 5.3 miles per hour.

The impact speeds at modern classification yards are controlled by computers and automatic braking devices. Thus, the coupling speeds at

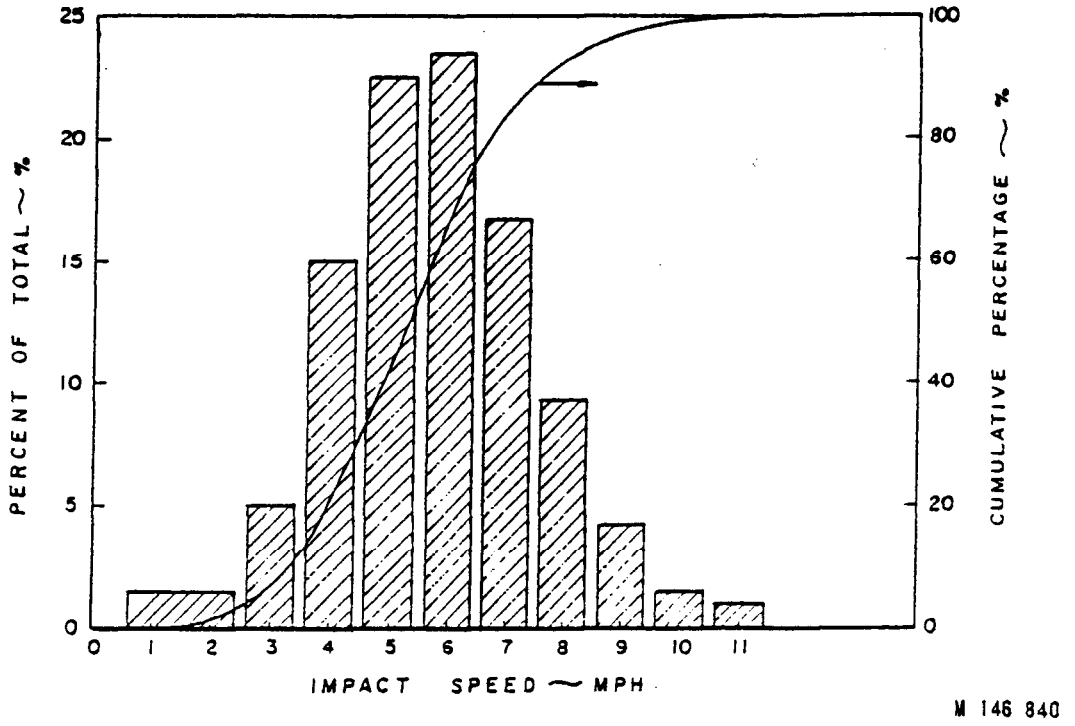

Figure 16. --Distribution of impact speeds based on 4647 observations (51).

these facilities should be controlled within closer tolerances. In most of these facilities, a controlled impact speed of about 4 miles per hour is sought. However, many factors still influence the actual impact speed and wide variations are possible. Some of these factors include grease on the wheel surfaces gripped by the retarders, differences in rolling friction between cars, wind, snow, and other weather conditions, varying track conditions, and malfunctioning controls. Data could not be located describing the distribution of impacts at a modern classification yard. It can be assumed, however, that the impact speeds for modern automated yards will be lower than those encountered in non-automated yards. Since there are still many small classification yards where switching is performed, on level or flat ground, the data of figure 16 can be considered representative of these operation.

Controlled Impact Tests

Full-scale impact tests have been conducted to evaluate many different factors. In most of these tests, the loaded test car, acting as the hammer, is impacted into a string of standing cars. In other tests, the

test car is at the head of a string of cars and a fully-loaded moving car impacts the test car. This latter case is analogous to the test car acting as the anvil. The most recent procedure is to let the test car run into a group of three coupled and fully loaded cars. Although the loads are similar in both cases, this method results in the highest loads. The variables in the controlled tests include draft gear or cushioning device, car type, and lading type and configuration.

Rigid lading, such as steel billets attached to the cargo floor, is generally used in impact tests to determine the structural integrity of the cars since it imposes the highest loads on the structure. Resilient-type carton lading is used when it is desired to determine the loading on the cargo.

The impact load is applied through a draft gear attached to the coupler of each car. The draft gear is a device installed between the coupler and the car body to absorb the energy of impact and to control the load imposed on the car body and freight. Draft gear designs vary from the so-called standard draft gear, which is a spring-friction damping device located in the back of the coupler that allows the coupler to compress or extend 2-5/8 inches on impact, to the 30-inch cushion underframe which allows 30 inches of hydraulic cushioning travel during impact. In between these extremes, there are many other variations.

In a previous study of the railcar coupling environment (35 , 37), the data were summarized in the form of shock spectra. This was considered the best data format for describing the complex motions recorded on the cargo floor, and is useful for describing the loads imposed on equipment rigidly mounted to the car floor. For general cargo which is not attached to the floor, the lading force or end-wall force is more meaningful. End-wall force is a measure of the cargo's compressive force on the end wall of the car as the car is brought to a stop. Since most cargo has some slack in it, it is free to slide or move once it overcomes floor friction.

One of the earlier reports of the effects of impact on lading for various cushioning devices is reported by Baillie (4). Since cartoned, canped goods represented a wide range of lading types and incurred a high damage ratio, the testing program concentrated on this lading. The test car load generally consisted of 1,700 cartons, each containing 24 cans, for a total weight of 53,300 pounds. The empty car weighed 45,600 pounds for a total rail weight of 98,900 pounds. In addition, empty boxcars and boxcars with only a single column of tamed goods were tested. End-wall loads and individual carton loads were monitored.

Since boxcars are normally loaded to near their capacity, and this condition results in the severest loading, only that portion of the data dealing with full loads is reported. Cargo conditions varied between a

dense loading configuration and one with slack space at the impact end of the car. A schematic of the progression of the impact forces through the fiberbox container load showed the peak lading force occurred at the forward one-fourth of the car and dropped off beyond that point.

The conclusion from this early study with tamed goods was that the force on the containers at the impact end and throughout the car are the indirect cause of lading damage. The end-wall forces caused little direct damage in one single impact. The lading damage normally occurred as a result of repeated impacts in which the first impact caused slack to develop at one end and succeeding impacts caused the cartons to become so disarranged in this slack space that they finally toppled over. Damage resulted from the fall or subsequent crushing by other cartons.

Van Der Sluys et al. (50) investigated the performance of various long travel underframes. The test car in this case was a 70-ton boxcar having a light weight of 77,500 pounds. Canned goods were used as these again represented one of the highest damage categories of high volume commodities. Tomato juice in cans and cartoned 24 to a fiberboard container were used. Two loads were used: one 5 layers high weighing 77,000 pounds and another 2 layers high, weighing 31,000 pounds. (9 cartons wide in a standard brick pattern). A 1- to 2-inch clearance was provided at the impact end to simulate normal conditions prevailing in a car in service. Data for a test car with a 30-inch cushioned underframe showed the bottom tier or carton layer imposed the highest end-wall force with a duration of over 400 milliseconds. The cushioning device showed a loading duration of approximately 300 milliseconds.

Van Der Sluys et al. (51) also reports on the performance of trailers on flat car (TOFC) and containers on flat car (COFC) arrangements in yard impacts. In these tests, the test car acted as the hammer car and impacted a string of three loaded hopper cars. Lading consisted of rigid and nonrigid canned goods (tomato juice cans and fiberboard cartons). The cartons were loaded to a 65,000-pound gross weight in standard block patterns. Prior to testing, a reverse impact was performed to provide a l-inch clearance from the end wall. Peak end-wall forces as a function of impact speed for the trailers attached to rubber cushioned kingpin stanchions and for containers having three different protection systems are reported. The different container protection systems included cushioned rub-rails systems employing rubber pads in shear (for up to 8-inch nominal movement), fixed container brackets and 9-inch end-of-car hydraulic cushioning, and fixed container corner brackets and 20 inches of underframe hydraulic cushioning. Peak end-wall forces up to 50,000 pounds were recorded. For a given impact speed, the cushioned underframe produced the lowest end-wall force, followed by the end-of-car system, and cushioned rub-rails. The trailer end-wall force was higher than that for containers with cushioned underframes, but lower than that for containers with end-of-car devices.

Peterson (40) summarizes the results of impact tests conducted by Pullman Standard. In one series of tests, a 40-foot boxcar containing 11 removable bulkheads was used to evaluate the effect of load dividers as a means of reducing force levels. The car was loaded to 51,200 pounds with cartoned can goods and impacted with a 169,999-pound hopper car having a variable stroke cushioning device (up to 3 ft). Impacts were made with the load divided into 12, 6, and 3 compartments. The results are shown in figure 17 for an impact speed of 10 miles per hour. It can be seen that the load reduction is not proportional to the number of compartments.

Peterson (41) also reports on the results of static compression tests for various canned goods in fiberboard cartons. Maximum compressive

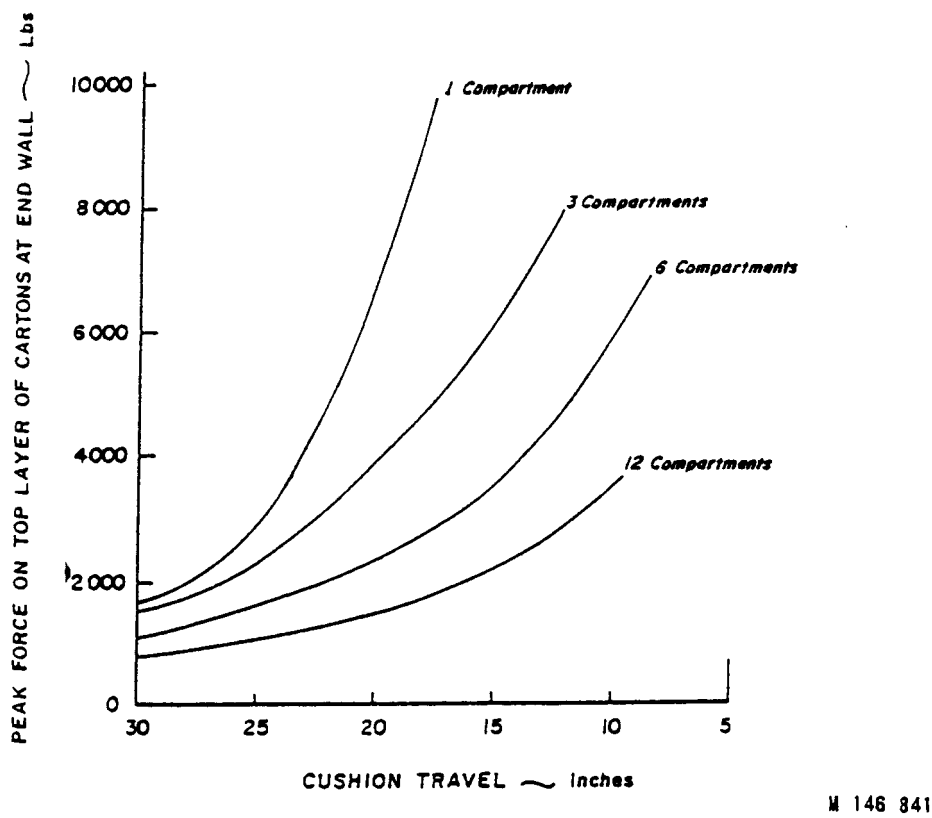

Figure 17. --Effect of compartment on end-wall loading for 10 mile per hour impact.

load (lb/ft^2), i.e., the point where pressure on carton and corresponding deflection ceases to be linear, ranged from 440 to 2,600 pounds per square foot. These values are used to predict the survivability of various carton loads for various impact speeds. Peterson (40) summarizes railcar impact data in terms of unit loading. These data are shown in figures 18 and 19 in which end-wall loads are converted to unit loads, i.e., pounds per square foot for boxcar data and COFC/TOFC test data, respectively.

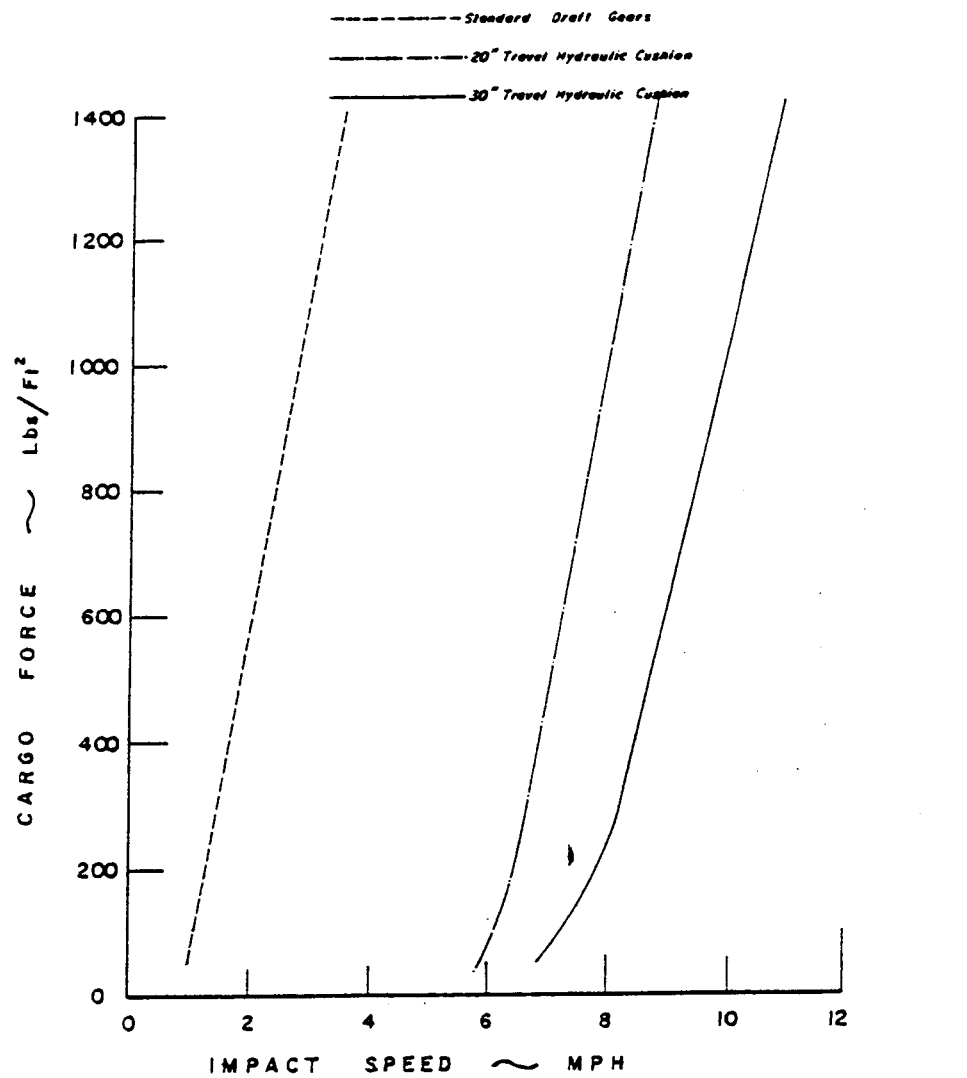

Figure 18. --Cargo force versus impact speed for boxcars having different cushioning systems.

Patterson (38) reports on impact tests conducted with industrial shipping sacks. In these tests, 600 bags each filled with 100 pounds of salt were loaded into the test car. The bags were packed 20 long by 6 wide by 5 high with the length parallel to the car. The hammer or impact car was a hopper car loaded to a rail weight of 169,000 pounds. The major bag damage, due to impact, took place in the first three rows on the impacted end, averaging over 50 percent failure at 8.6 miles per hour. The measured end-wall forces ranged from 20,000 pounds for a 4 miles per hour impact to 130,000 pounds for an 8 miles per hour impact.

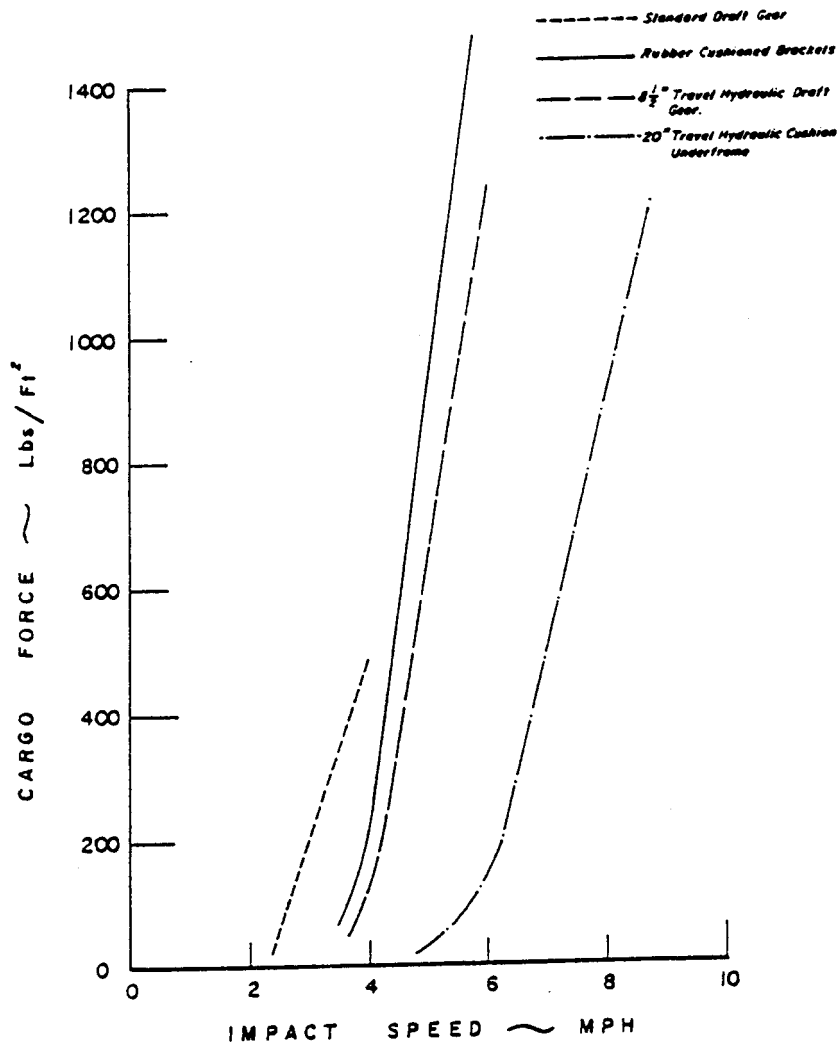

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Figure 19. --Cargo force versus impact speed for containers on flatcars (COFC) with different cushioning systems.

Data are presented (3) in terms of lading acceleration for a variety of draft gears and impact speeds. Accelerations *were* recorded on both rigid and resilient lading (canned goods) at the center of the car. Typical oscillograph records are presented showing pulse shape and duration. Typical lading acceleration for an 8 miles per hour impact was approximately 10 g for a duration of 30 milliseconds with a standard draft gear. Lading acceleration for a 24-inch travel gear was about 2.3 g with a duration of 250 milliseconds for a 12 miles per hour impact.

The data show that the factors which affect container loading during impact are: the railcar cushioning device, the weight of the cargo and the car body, the internal friction of the cargo, the number of subdivisions, and the area of cargo in contact with the end wall or subdivider. These factors have been studied and detailed information on their effects is available in the various references. There are also many possible combinations of cars, equipment, and conditions which will influence the railcar coupling shock, that have not been investigated. These include the various cargo types, type of car, cushioning, number of cars, etc. Computer simulation programs have been written to analyze the effect of the large number of variables and their possible combination. Good correlation with field experimental data is reported with these programs (28 , 39) and thus can be expected to fill in some of the data gaps for this hazard.

Assessment of Railcar Shock Data

The data available to describe the dynamic loading on cargo as a result of railcar coupling operations are extensive. The cargo forces in terms of longitudinal container loading are well defined for a variety of railcar equipment and impact speeds. Based on a particular product/package compressive strength, it is possible to determine the impact speed at which damage will occur for specific railcar equipment. Additionally, the benefits of subdividing cargo into compartments via load dividers can be estimated and the impact speed for damage under these conditions can also be estimated. The impact speed distribution curve will provide an estimate of the percentage of cars likely to be impacted at or above the speeds at which damage will occur. Thus, estimates can be made of the potential for cargo damage and/or the associated risks. The impact speeds presented are based on a single classification yard.

The overall probability of a particular car receiving an impact at a given speed will depend on the number of classification yards passed, but an estimate can be made if certain assumptions are made, e.g., the impact distributions are the same for each yard. This procedure is outlined in (33).

The procedure outlined above is considered adequate for most cargo. However, in addition to the longitudinal compressive loading during impact, there is also a superimposed acceleration. This acceleration can be critical for some cargo. Unfortunately, most railcar impact studies involving resilient cargo have not recorded cargo acceleration and compressive loading. All cargo, regardless of its sensitivity, is exposed to both of these effects and must be considered for proper package design and/or evaluation.

TEMPERATURE AND HUMIDITY

The climatic conditions of temperature and humidity are important considerations for paperboard and plastic containers and components, but are relatively unimportant for wooden containers or steel drums. The strength of paperboard products is significantly reduced because of moisture while temperature is more significant with regard to creep of plastics.

Temperature and humidity can usually be monitored and/or observed directly, particularly in storage and warehouse areas. Other portions of the distribution cycle are more difficult to monitor and must be estimated unless, of course, they are controlled e.g., refrigerated car. One source estimates temperature within a standard freight car at a maximum of 30° F above ambient conditions. Another estimate uses a 1° F rise in temperature per 24-hour period for a precooled insulated boxcar, standing or moving, under a hot sun. Thus, each situation has unique equipment and conditions which must be considered when establishing temperature and humidity conditions.

Temperature and humidity conditions encountered by general cargo in typical distribution cycles are difficult to summarize because of the many factors which influence not only the ambient conditions, but cargo response as well. A large amount of effort has been expended by various organizations and agencies compiling ambient temperature and humidity data and other climatic conditions. It has been common practice by many packaging people to define the distribution temperature and humidity conditions in terms of ambient conditions and assume cargo is in equilibrium with these conditions. In some instances, analysis or laboratory testing is performed to more accurately determine the cargo response to these inputs. For others, the ambient conditions are assumed synonymous with cargo conditions. This latter assumption may be justified, but it is important that those making that assumption are aware of how the data are acquired. For example, temperatures published by the Weather Bureau are recorded in shaded, ventilated shelters with louvered sides to eliminate wind and sun effects. These measurements could apply to a well ventilated, unheated warehouse. Determination of cargo conditions for other situations must take into account those factors which would

cause a variation between ambient and cargo conditions. In many of these situations, the ambient temperature and humdity data must be supplemented with other data including expected solar radiation and wind conditions.

Descriptions of the ambient temperature and humidity conditions, including maximas, minimas, and probability of occurrence are available and are considered quite accurate (37). These data are based on weather data recorded for many years at various locations throughout the country. Similar data are published in other documents (1 , 12 , 25). A more concise description and one which has been used and applied to military cargo and hazardous materials is to specify only the extremes to which cargo is exposed (including maximum cargo response). These extreme descriptions, although realistic, are considered overly severe and not applicable to general cargo.

The difficulty in describing or summarizing temperature and humidity conditions in terms of cargo response is due to the many variables which influence the cargo's response to the climatic inputs. Some of the more significant variables include cargo weight, cargo specific heat, thermal conductivity, configuration, surface absorptivity and emissivity, and ventilation or wind. In addition, there is the movement of the transport vehicle with resultant air flow, there are changes in locality and corresponding ambient conditions, all at various rates. A severe condition and the one used by the military is to assume the cargo is protected or shielded from the wind and at the same time, exposed to maximum solar radiation. Under these conditions, it is possible for the cargo surface temperature to reach 160° F.

The range of possible conditions that can be encountered in a typical distribution cycle has limited the number of studies that have been conducted to acquire general cargo response information. For the most part, those measurement studies that have been conducted have been performed for a very specific situation or set of conditions. Additionally, the unavailability of suitable instrumentation has hampered the acquisition of extensive data. Temperature measurements within a cargo load require a remote sensor and a continuous recorder. such units should be self-contained so that they can be used for measurement on or in cargo during transport. A compact unit of this type is not commercially available. Several prototypes have been developed by the U.S. Army Natick Laboratory and the U.S. Air Force Package Evaluation Agency and are being used for very select projects. Humidity measurements and data acquisition present problems similar to those for temperature recording. However, in addition to those problems, there is the need for an accurate humidity sensor. For a complete description, humidity should be described in terms of ambient air temperature and the concentration of water vapor in the air. The latter can be expressed in terms of relative humidity, a weight ratio (lb moisture per lb of dry air) or dew point temperature, all of which are interrelated. A sensor

which monitors relative humidity is available and is being used with the above-described military-developed recorder. A problem with this sensor is that it does not measure moisture content of material. This is a major disadvantage in studying moisture-sensitive packaging materials such as corrugated board, where structural properties are very sensitive to moisture content. The moisture content of corrugated board, however, can be related to air relative humidity. This relationship is relatively independent of ambient air temperature. However, a period of time is required for the board to reach equilibrium. If rapid changes in air temperature occur, the air relative humidity will change fast, while material moisture content would change at a slower rate. Further, under certain conditions, the moisture in the air may actually condense on the cargo either as a result of a 100-percent air humidity condition or because the cargo is slow in following air temperature and is at the dew point temperature. Under these conditions, air relative humidity would not always be an accurate indication of material moisture content.

As indicated earlier, it is theoretically possible to predict temperature and humidity conditions of the cargo based on ambient conditions. This has been done in some isolated studies. Controlled laboratory tests have been conducted to determine cargo response. Specific studies to monitor cargo response during storage or transportation, or even to monitor the ambient conditions within the transport vehicle or warehouse, are extremely sparse. Most of these have been summarized (37). More recent studies are summarized in the following paragraphs.

Barca (5) presents data on the conditions of temperature and humidity inside various fiberboard boxes during shipment, warehouse storage, and outdoor storage. Data were collected with the Natick-developed humidity/temperature recording system which is capable of recording temperatures from -40° to 65° C and relative humidity from 10 to 95 percent.

Initial shipping tests via truck and airmail involved a single 16- by 12- by 10-inch fiberboard container weighing 20 pounds. For these tests, the sensors were placed inside the package. The tests which were conducted in November and December resulted in temperature swings from 47° to 70° F and relative humidity variations from 21 to 85 percent. Measurements were not correlated with ambient conditions. Another test program involved shipments from Charleston, W. Va. to Rota, Spain via Navy ship. The loads consisted of fiberboard can cases stacked on wood pallets. Measurements were taken on the top tier center case and on the third tier center case of three pallets. Representative data showed relative humidity varied between 25 and 75 percent.

Warehouse storage conditions were monitored at Tracy, Calif. The primary objective of this effort was to determine if a significant temperature gradient existed between various levels of a four-pallet high configuration during normal warehouse storage. Temperatures were recorded on the external top surface of a carton 15 feet above the floor, the external

surface of a middle carton 8 feet above the floor, the internal top surface 15 feet above the floor, and an external bottom surface 3 feet above the ground. The data showed significant temperature differences between the following locations: (1) external top and external middle, (2) external top and external bottom, (3) external middle and internal top, and (4) external bottom and internal top. Data on cargo response to outside storage conditions were also reported. However, this effort was directed toward determining the causes of condensation within shrink film unit loads. The results showed that direct exposure to sunlight, and not prevailing outside humidity, was the major factor causing moisture to collect on the top inside surface of the enclosed unit load. Humidity paralleled temperature fluctuations, but they were not proportional.

Knobbout (29) describes the results of a study to determine the condensation risks involved in marine transportation of containerized cargo. Both experimental and theoretical evaluations were performed to determine the factors which influence condensation for a typical cargo consisting of metal cans in corrugated fiberboard boxes. Temperatures at various cargo positions within the containers and of the ambient air were recorded. The potential for condensation was determined analytically based on the ambient humidity conditions at time of loading. The moisture content within the cargo container was assumed constant for the trip and the potential for condensation determined from temperature differences alone. Apparently, equipment for humidity measurements were not available. Corrugated fiberboard boxes are reported to have a large influence on the condensation of water in a container.

Fiberboard is thus regarded as a major moisture source in the container. It can emit large quantities of moisture which may then condense in other places throughout a container. This condensation can cause damage to the cargo loaded in containers. It is reported that this type of damage can be prevented by specific measures aimed at an equal temperature distribution throughout the container. The steadier the product temperature and the more quickly the temperature inside the container adapts to the changing ambient temperature, the lower the condensation risk. On many of the routes studied, pallet stacking with resulting air circulation reduced the otential for condensation. It is suggested that land transport with resulting greater speeds and temperature changes may present more of a risk with respect to condensation problems.

A discussion of the relationship betwen the ambient temperature extremes and cargo response is presented by Fridringer et al. (17). It is stated that if worst-case geographical areas during worst-season exposures are assumed, container material temperatures in excess of 200° F and lower than -70° F can be considered possible in the United States.

Assessment of Temperature Data

Extensive data are available to describe cargo temperature both in terms of ambient weather conditions and cargo response for specific application. The latter category includes measurements both inside containers and on the surface of the cargo. Application of any data to specific situations must be made with caution. Data have shown that the cargo temperature can lag behind ambient temperature fluctuations because of the thermal inertia of the cargo, or it can exceed the ambient temperature because of direct solar radiation to the cargo or to the vehicle or warehouse. The temperature in the cargo compartment of an aircraft parked on a ramp in the sun, for example, will be much higher than the ambient temperature. Conversely, a moving vehicle will usually record lower temperatures for hot days because of its motion, or in winter the internal temperatures may be higher.

The available data are inadequate at the present time to describe cargo temperature for all situations. However, representative data are available for specific situations and can be used as a guide for estimating cargo temperature. Cargo temperature can also be readily measured with commercial equipment and is easily accomplished. Alternately, analyses or laboratory tests can be performed to determine the response of specific cargo. It is considered unlikely that cargo temperature conditions for all possible situations will ever become available due to the many variables which affect cargo response.

Assessment of Humidity Data

The same assessment can be made of humidity data as for temperature data. This hazard, however, is not as easily monitored and recorded. Accurate humidity sensors for ambient air or moisture sensitive materials are not readily available. Ambient humidity conditions may be used for cargo stored in unheated, ventilated cargo spaces under slowly changing conditions. The data would not be applicable to cargo in closed containers, vans, or freight cars where the moisture content is relatively fixed and rapid external changes in ambient temperature can result in condensation on the cargo and/or walls of the transport unit.

The ambient relative humidity has a significant effect on the load-carrying capability of corrugated boxes, particularly with respect to the stacking strength. The ambient relative humidity is the driving force which determines the moisture content of the box material. Container load carrying capability is directly related to the moisture content. The rapidity in which moisture in the air penetrates the container material has been studied by Ievans (26). Ievens determined

from relative humidity measurements inside corrugated containers, in various positions in a pallet load under fluctuating ambient relative humidity conditions, that the containers assume a moisture content closely related to the average ambient relative humidity. Based on these results, detailed information on the short-term variations of ambient relative humidity is not considered critical to establish the strength of palletized corrugated boxes. Further study in this area for individual containers is needed.

COMPRESSION

Cargo compressive loads are generally associated with warehousing and storage stacking. These static compressive loads are a result of stacking one container on top of another up to some reasonable height. Stacking height can vary considerably depending upon available headroom or ceiling height, storage equipment (including the use of storage racks or of a limited lift height fork truck), stability of the stack, or general procedure regarding maximum stack height.

Warehouse stacking heights can easily be determined by observation of storage facilities (equipment and ceiling height), including stacking procedures. These are static loads and can readily be considered in package design and/or testing. Dynamic compressive loads resulting from transportation are more difficult to establish. Load amplification can occur as a result of vibrations at critical resonant frequencies. Godshall (20) reports amplification factors of 6 for corrugated cases, while O'Brien et al. (34) report factors up to 4 for fruit in cartons, for sinusoidal vibrations typical of transport vibration frequencies. These amplification factors when applied to the static compressive load can result in extremely high dynamic loads on the bottom containers, even for the low stacking heights in vehicles. In addition, there are the quasi-static loads resulting from ship low frequency motions (pitching and rolling) and aircraft response to updrafts or gusts. For a ship with high stacking height, these loads can be significant. A 1 g acceleration will add the equivalent of a static load twice that existing on the bottom container.

Longitudinal dynamic loading due to railcar coupling is another source of compression loading. These loads are discussed in the section entitled "Railcar Coupling." In addition, there are the loadings due to mechanical handling equipment. These include the squeeze clamps on lift trucks, slings, and cargo nets. Compression due to strapping, banding, or other restraint systems is another source.

Sobczak (49) reports on side-to-side or end-to-end loads on containers as a result of carton clamp, material handling equipment. Although the study was directed toward reducing damage to corrugated cases due to excessive clamping forces, the data can be used to establish typical

clamp load ranges. Using a typical system efficiency of 75 percent, a hydraulic pressure range of 1,500 to 1,800 pounds per square inch, and a cylinder effective cross-sectional area of 2.5 square inches, the side-to-side clamping force that is applied by the platens can range from 2,810 to 3,380 pounds. The side platens are normally self-alining such that uneven loading of containers is minimized. The side-to-side compressive load is carried by the containers in a reamer similar to a machine compression test, since the platens fully cover the containers. If the platens do not cover the containers, their load-carrying capability is reduced. This latter condition is analogous to the reduced stacking capacity (compression in the vertical direction) as a result of pallet overhang.

It should be mentioned that these are nominal values. Each clamping system is unique in that it is designed for a particular unit load size, weight and material friction coefficient. Thus, these values should only be considered as representative.

PUNCTURES AND ABRASIONS

Punctures and abrasions are highly visible effects, but they are extremely difficult to define in quantitative terms. In some respects, they are indirect results of other hazards. Punctures are a result of a package falling onto a corner of another, or the reverse; nails or hooks projecting from a surface and penetrating the outer container; or the misuse of handling equipment such as a forklift truck tine penetration. Abrasions are the result of dragging a container on an abrading surface; sliding down a chute, rubbing by a moving conveyor belt; sliding on the floor of a vehicle as a result of sudden stops or starts; or the relative motion between stacked containers caused by vehicle vibration.

A review of several studies investigating these hazards is presented (37). Based on the results of these studies, it does not appear that puncture or abrasion represent a significant damage-producing hazard.

DISCUSSION OF DATA

Considerable data and information are available concerning the common carrir shipping environment. For many reasons, however, much of the reported information is not useful because it is in a form not considered applicable to general cargo descriptions. Further, many of the investigations have been performed to study specific system conditions or products. Data analysis procedures and presentations have also varied, making comparison difficult. In spite of these factors, data are available to adequately define the environment for many of the potentially hazardous conditions. In some instances there is correlation between

different sources providing increased confidence in the descriptions. Statistical data are also available for some hazards allowing a risk oriented and/or economic optimization approach. These data are considered most useful for commercial cargo where economic considerations usually dominate.

The data for handling loads have been presented in a format considered useful for design purposes. This format (fig. 1) presents drop height data statistically, giving magnitudes and frequencies of occurrence of drops for a typical distribution cycle. A design procedure for determining the optimum design height based on data of this type for several products is shown in figure 20, and illustrates how different drop heights can be arrived at for the same handling conditions. The curves are based on the assumptions that (1) the statistics on handling loads apply regardless of product value and (2) the fragility rating or sensitivity to damage is the same for all products. The curves are plotted in terms of dollars versus design drop height. C_p represents the packaging cost which is shown to increase with increasing drop height in the manner shown, since higher drops will require more cushioning, larger containers, and higher shipping costs. C_R represents the damage cost or

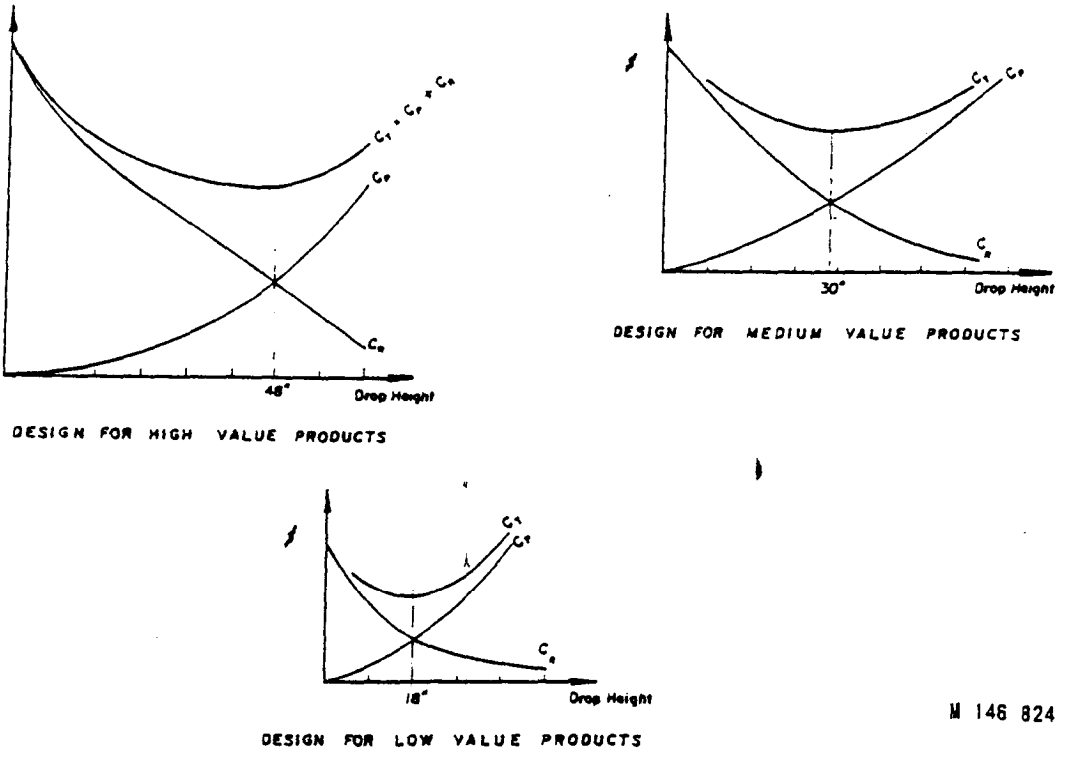

Figure 20. --Package cost versus design drop height for high, medium, and low value products.

Cost to repair or replace the product, and is shown to decrease with increasing design drop height as a result of the reduced probability chat packages will be dropped from a height greater than the design height as shown by the statistics. This latter curve can also include costs assigned to goodwill as a result of any damage. The total cost curve, C_T, represents the sum of the packaging and damage costs. The optimum design drop height is shown to be the point of minimum total cost.

Three curves are developed to show different optimum design drop heights for packaged products having different values but exposed to identical handling conditions. These results could not have been obtained by an estimate of maximum drop height. Thus, although estimated maximum drop height based on typical handling operations may have some rational basis, it is only a guess and does not provide the statistical data necessary for an optimum design approach. Unfortunately, there are very little data currently available concerning the statistics of handling loads on which to base an economic design. Much more information is needed concerning the handling load statistics for specific handling operations and/or typical distribution cycles before a design approach of this type can be implemented. More detailed information is also needed to show the effect of package size, weight, and shape, including pallet and other unit load configurations. Additional information is required concerning the effects of labels, handholds, and the distribution of the drops over the various faces, corners, and edges.

The vibration environment on transport vehicles is difficult to describe in simple terms since it is extremely complex involving many excitation frequencies, each of varying magnitude and phase relationship. Current vibration studies have reported data in terms of PSD. Power, as the term implies, is the rate of doing work and for a harmonic vibration it is proportional to the square of the amplitude. For the transportation vibration environment, which is composed of a large number of harmonic vibrations, the initial analysis consists of measuring the total power, or the sum of the power of the component vibrations. A PSD plot shows how this total power is distributed as a function of frequency and is defined as the power per unit frequency interval, This data format has application for sophisticated analysis and laboratory test purposes, but is not in general use by packaging engineers. Power spectral density data, however, show the frequencies containing the greatest energy and their energy levels. These energy levels vary from one transport mode to another and, therefore, require individual description. Truck vehicles show the highest energy levels in the low to medium frequency range, while aircraft show the highest energy levels at high frequencies. The ship environment shows the lowest levels of vibration and may account for the sparse data on shipboard vibrations.

Translation of a PSD envelope to an acceleration envelope requires certain assumptions. Power spectral density data can be converted to

g_{rms} versus frequency if the bandwidth used in the analysis is known. However, the distribution of the acceleration peaks in a particular bandwidth can vary considerably and still produce the same g_{rms} value. The maximum acceleration spread or range is 3 to 4 times the g_{rms} value for a true normal distribution, but has been reported to be as high as 10 for measured field data. Statistical data showing actual peak distributions show a wide separation between the peak value and the level at which there is some resemblance to a normal distribution, typically 99.5 percent probability level. It is at the 99.5 percent level that there is good correlation with the peak acceleration levels computed from PSD envelope data using a factor of 3 times the rms g level, and are the levels presented in the acceleration summary curves. The actual peak values (extremes) are considered to occur so infrequently that they have not been incorporated in the descriptions. Until there is some correlation between a sinusoidal vibration input level and a random vibration input level (corresponding to the PSD envelope tune) with respect to general cargo damage or response, the acceleration summary envelope curves presented previously are considered the most useful interim descriptions.

The shock environment on transport vehicles has been reported in several forms ranging from shock spectra computed from cargo floor motion, to frequency spectra of cargo floor motion, to cargo response to shock inputs. Descriptions in terms of shock spectra are based on the assumption that cargo is in contact at all times or is attached to the cargo floor. If the natural frequency of the cargo is known, it is then possible to predict maximum cargo response. Descriptions in terms of vibration frequency spectrum (of an empty vehicle) are based on the assumption that cargo will respond appropriately (i.e., cargo will bounce) if the vibration descriptions include transient inputs. The descriptions would necessarily be in terms of a random vibration input since it is obvious that the vibration levels shown by the summary envelope curves would not produce package bounce. The extreme peak values shown by the statistical vibration data can be attributed to a shock input and are probably the cause of package bounce. Shock description in terms of a temporary increase in vibration level has also been proposed. This latter description is based on the similarity in shape of the vibration spectrum for the event and for the period preceding the event with the exception of a much higher energy level. Description in terms of cargo response is an attempt to describe loose cargo motion or bounce.

Cargo response measurements have shown cargo is exposed to a type of repetitive shock input (due to bouncing) with a superimposed vibration background. The shock environment is described in terms of number of shocks and corresponding magnitude (g-level) for a specified time. It is suggested that these transport shocks be simulated by a repetitive shock machine. Unfortunately, the data apply to a particular vehicle

traversing a severe test course. Although many descriptions of the shock environment are available, additional effort is required either to establish the adequacy of *existing* descriptions (vibration), or to generate data applicable to general cargo on commercial vehicles (i.e., cargo response data). Until one or both of these is accomplished, shock descriptions can be considered inadequate.

Railcar coupling represents a distinct and discrete shock event easily separated from other transport shock events. The primary effect on cargo due to railcar coupling would appear to be the external longitudinal compressive load on containers as the car is brought to a halt.

However, in addition to this compressive load, there is a superimposed acceleration pulse. This pulse is not the same as the car floor, since first the containers slide and then impact. During the sliding, some of the energy of impact is absorbed in friction. Thus the acceleration on the package is less than the car. Only limited data are available concerning cargo accelerations, while extensive data are available concerning compressive loads. End-wall force measurements have not been correlated with cargo accelerations. Typical cargo accelerations are reported to be 10 g at 30 milliseconds for standard draft gear and 2 g at 300 milliseconds for long travel draft gear. End-wall force measurements show much longer durations. Compressive loads and accelerations within containers at various locations within the car and for partial loading are needed for improved load descriptions. It should be mentioned that the longitudinal accelerations may cause damage to products while the container survives the compressive load and appears undamaged.

Compressive loads on containers, at least those caused by the static topload, are easily detemined by observation or by direct measurement. The dynamic compressive loads are more difficult to measure since the loads are a result of dynamic conditions or motions. Dynamic loads occur as a result of: low frequency vertical and lateral accelerations, vibration close to system natural frequency with resulting amplification, and horizontal deceleration. The low frequency accelerations are a result of rocking of transport vehicles or the slow pitching motion of a ship. Typically, these values are on the order of 1 g, causing a doubling of the equivalent static load. Vibration resonances can result in a topload magnification of five or greater. Horizontal decelerations such as occur during railcar impacts impose compressive loads dependent on a number of factors. Except for railcar coupling, these dynamic compression loads have not been measured directly. Rather, the loadings have been inferred by indirect measurements, i.e., cargo acceleration. It should not be assumed that the effects of dynamic loading can be fully described or even simulated by an equivalent static load. Factors such as product acceleration and product/package fatigue must also be considered.

Cargo temperature and humidity conditions are a direct function of ambient conditions unless, of course, there is a controlled environment such as exists in refrigerated cars or heated warehouse. Temperature and humidity data are readily available and can be described statistically in terms of ambient conditions. Cargo response to these conditions has been determined for specific cargo, storage, and transport vehicles. For other conditions, cargo response can be determined through analysis, laboratory simulation, or field measurement. In general, the cargo in unheated warehouses or transport vehicles does not experience the temperature swings that occur in the ambient air. Thus ambient air temperature is a conservative estimate of cargo temperature, particularly since in most warehouses and vehicles, the cargo is shielded from direct solar radiation.

Humidity is a much more difficult hazard to define. Long periods of exposure to constant relative humidity are required of paperboard products before equilibrium is reached. Thus, there is even a lesser swing in cargo relative humidity when compared to ambient relative humidity than occurs between ambient and cargo temperatures. An extreme condition for cargo occurs when closed containers or vans undergo rapid temperature changes. The humidity in the van or container can condense directly onto the cargo or water may drip onto the cargo as a result of water condensing on the container or van walls and ceiling. Alternately, the cargo may remain at a low temperature during air temperature swings with the result that it is at the air dew point temperature and causes the air moisture to condense on its surface.

CONCLUSIONS

Many of the hazards encountered by cargo during shipment via common carriers can be described on the basis of available data. In some instances the data are very extensive and the hazards can be described statistically providing an economic or risk-oriented approach. In other cases, the data are sparse or are in a form not useful for design or test purposes. Transportation shock is in the latter category, but it can be assumed this hazard can also be defined by directing appropriate effort. However, before any extensive measurement program is initiated, it is desirable to identify the specific hazards causing damage to cargo and determine their relative importance. It should be recognized that some hazards will be more damaging to some products or packages than others.

In spite of the lack of detailed information on all aspects of the common carrier shipping environment, cargo has been distributed for many years with varying degrees of loss and damage. Laboratory tests are conducted and provide a reasonable estimate of performance. Trial shipments are also made and after minor modifications, a successful and

economic package is developed. However, in order to use new and existing packaging materials in the most efficient and effective manner, it is essential that accurate and detailed information on the shipping hazards be available. The end result could be substantial savings in material and/or reduction in product damage.

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