A CRITICAL ANALYSIS OF VIBRATION MEASUREMENTS OF THE TRANSPORTATION ENVIRONMENT

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JANECE RAE HAUSCH

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ABSTRACT

A CRITICAL ANALYSIS OF VIBRATION MEASUREMENTS OF THE TRANSPORTATION ENVIRONMENT

By

Janece Rae Hausch

A review of vibration and its occurrence in the transportation environment is presented. Details of the analysis and presentation methods used are examined. Examples of real damage situations are given. Implications of vibration's interaction with the package system and the need for exact information on input levels and frequencies is stressed. A comprehensive comparison of three recently published reports measuring the environment was made. The two studies conducted by the School of Packaging using commercial vehicles under actual operating conditions were found to have acceleration levels which fall within figures previously reported. This finding suggests that present interpretation of the actual environment is overly severe. The predominant frequencies experienced were higher than expected. Areas requiring further investigation for a better understanding in package design and current controversies concerning vibration inputs are defined.

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Janece Rae Hausch

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Every product is subjected to shock and vibration while proceeding through the distribution system. In general shock is usually a result of drops incurred during handling operations. Vibration is the result of input to the package through material handling equipment and transportation vehicles. The former is a controllable factor which can be measured for the individual manufacturing and warehouse situations. Transportation related vibration is of a more varied and uncontrollable nature relating to specific vehicles and operating conditions. Vibration occurs as the result of the interaction of the vehicle structure and the road surface.

The area of shock input has been extensively researched in order to relate product damage to material handling factors. These studies include the number of expected drops, their height, the weight of the package, and the relation of the cushioning material to the actual input to the product. Sophisticated engineers have utilized this information in the design of packages for protection. Unfortunately not all product damage is related to drop shocks but has been found to relate to the more complicated input of vibration to the product and its package.

It is important that the engineer understand the implication of the vibration response of the packaged product to the transportation vibration. This less intensive input damages the product through force factors due to amplification and fatigue. Abrasion can result in container loss due to an illegible address. An unsightly package loses customer appeal. Vibration may cause a breakdown of the package components so that it is unable to perform its protective function. This failure may have an effect on the external surroundings with possible damage due to leakage, loose product impacts, or broken container hazards.

A considerable amount of information has been published describing the vibration environment. Various studies were conducted to determine the extent of vibration in the field. These experiments represent a considerable undertaking from the standpoint of time and money. The modes of travel covered were truck, rail, air and shipping. This information is necessary for a scientific approach to the design of packages which would be able to withstand the distribution environment. With the proper data the design of a package can be evaluated to provide additional protection or eliminate costly over-packaging. An economic trade-off may be made between the package cost and cost of losses due to damage.

The previous work done in the transportation vibration measurement field has been full of inconsistencies and is inconclusive regarding the package environment. Many of the projects were of a limited nature such as the analysis of a new type of aircraft or suspension system. Although used as distribution data most measurements were not meant to examine the effect on cargo but on the structural integrity of the vehicle.

Government agencies have developed the most information on vibration but they have been mainly concerned with military and space vehicles. Some studies concerned directly with packaged product distribution have been conducted by the related transportation industries and packaging groups. Composite studies which combine the results of different vehicles and procedural methods compound problems and present extreme values. These studies have been sporadically conducted since the 1950's and many have been limited in scope according to the researcher's objectives and costs. Published literature reveals a wide range of values for expected frequencies and expected acceleration levels.

The vibration data presented is not static and must not be construed to be all inclusive of the transportation environment. There has been a constant change in vehicles and methods of operation. Many new modes of travel have opened up including cargo jets, high speed trains, piggy back, and container ships. These all present new possibilities of input to be measured and may be found to be considerably different than "normal" vibration inputs.

Beside the particular vehicles selected the methods used in the studies should be questioned. New measurement instrumentation and new faster methods of analysis have been developed, refined and utilized. Examination of the alternatives used and data collected will allow future researchers greater refinement since they will know what to expect and can anticipate problems.

To be useful to the engineer some sense should be made of the large amount of information available. Vibration information gathered should be of a general nature and presented in a practical form for use in engineering calculations. Conditions encountered should be representative of common transport environment applicable to packaging. Any composite data form should be compiled selectively so as to avoid overstatement and misinterpretation of the facts.

It is the intent of this paper to examine present published data representing values established for commercial truck and rail transportation. To begin with a general review of vibration will be given along with how this phenomena is measured. Following will be a review of the ways that the recorded information may be analyzed. Then the various formats for presenting the information and inherent problems incurred will be examined. Finally a detailed comparison is made of three of the most recent reports with appropriate conclusions and further considerations.

II. VIBRATION

Vibration is defined as an oscillating motion. The movement varies independently over time and magnitude. This motion is usually represented as a wave on a graph. The magnitude factor is designated the wave amplitude and is the maximum vertical distance through which the wave varies from the origin. The period of the wave is the amount of time required for the motion to begin repeating itself. The frequency of the wave is the number of wave cycles which occur in a second and is the reciprocal of the period. A pure sine wave has both a constant amplitued and constant frequency.

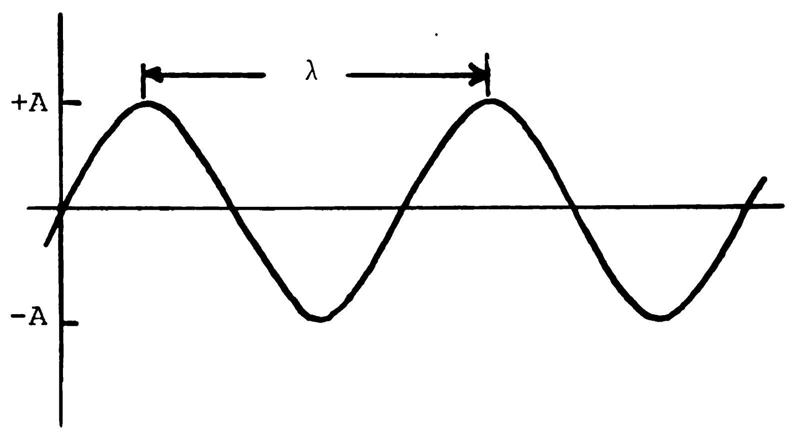

FIGURE 1.--Sine wave.

Complex waves can be formed by the combining of individual sine waves. The various input segments are added to determine the maximum amplitude and the frequency of occurrence. An example is shown in Figure 2.

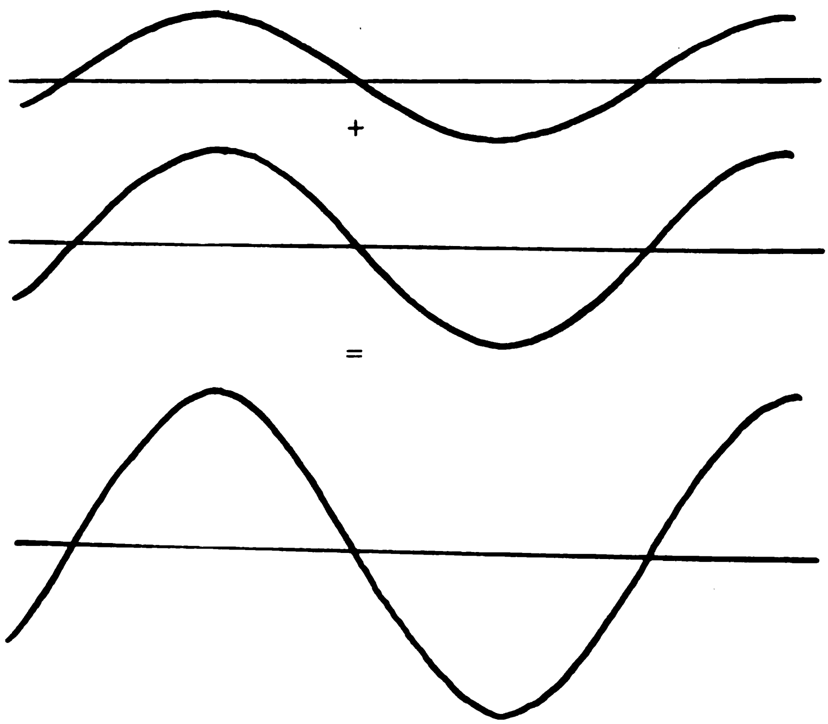

FIGURE 2.--Combined wave form.

Other common wave forms are the square wave and sawtooth wave. These occur as a result of the discrete properties of an object and its driving mechanism. In practice these may be simulated by a combination of sinusoids.

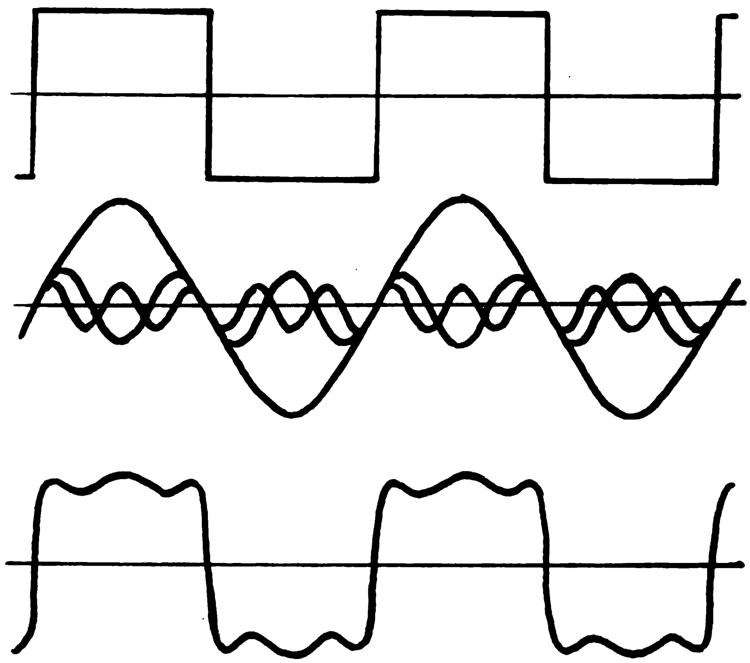

FIGURE 3.--Complex waveform.

Wave motion can be described as being stationary or nonstationary. The latter movements are called transients which are sudden changes in amplitude from the normal state such as occurs in a shock input. Since these occur only occasionally the important aspect is the time element or duration. Common causes of transient motion in the transportation environment are rail switching, rough roadbeds, and hard accelerations. The important factor is whether the package has time to react to the extreme input.

Stationary motion is described as being either periodic or random. A periodic motion repeats itself in a continuous pattern. In this case the important factors are the dominant frequency or frequencies of the input and their magnitude. Random motion is one which has no set pattern of either magnitude or frequencies. Since the motion is not exactly definable, the variable factors must be stated in terms of averages or maximums. It has been found that the transportation environment is basically a random situation with discrete inputs from the drive mechanisms and railbed plus variable inputs from interactions of the entire system.

The importance of wave motion is the manner in which a mass reacts to the input energy. Each mass has a natural frequency at which it reacts.

$$f_n = \frac{1}{2\pi} \sqrt{K/M}$$

The variable K is the spring constant or stiffness factor of the object or package. Many products have various components each of which has its own natural frequency due to its construction or mounting characteristics.

Energy input to an object from a wave of the same frequency as the object's natural frequency results in extreme amplification of the input force. This condition is called resonance. Of course an object does not respond at the theoretical limit at resonance due to the factor of damping. Damping is the dissipation of amplitude through the transfer of mechanical energy at different rates or into thermal energy. The amount of energy transferred to an object is seen in transmissibility curves for various fractions of critical damping.

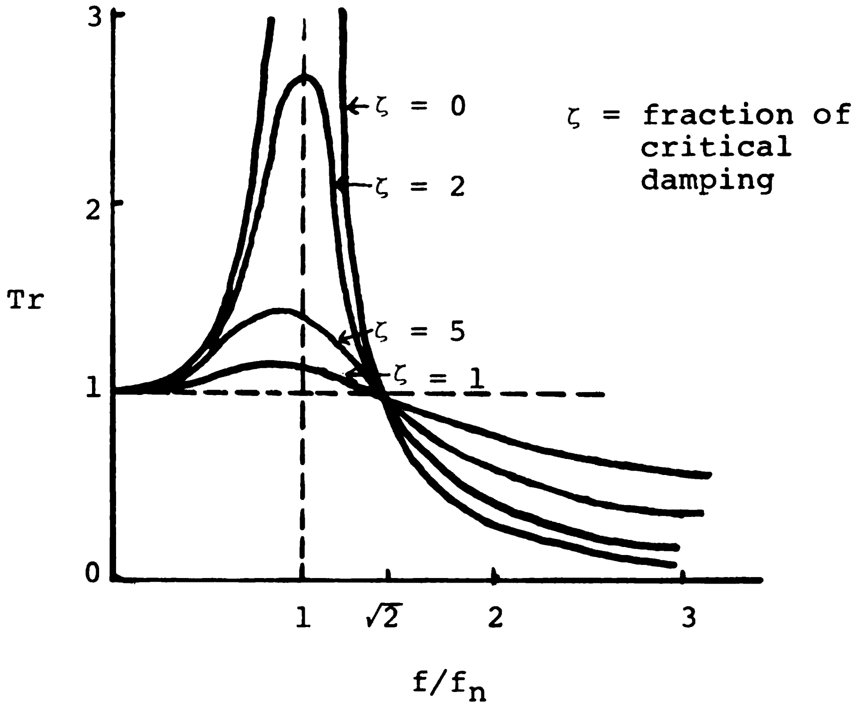

FIGURE 4.--Transmissibility curves.

As can be seen the force experienced by the object can be many times the input force. A ratio of forcing frequency to the natural frequency in the range of .5 to 1.5 causes serious magnification levels. Other factors affecting the response level at the resonance point are humidity and temperature. In these cases the characteristics of the packaging materials may be significantly altered. Corrugated absorbs moisture thereby losing strength, while cushioning material changes stiffness at different temperatures.

All parts of a product are affected by a dynamic input to the system. A transient input results in a vibration which occurs at the natural frequency. However, it quickly dies away due to internal damping and lack of continuous input. A periodic input results in the product vibrating at the particular discrete frequency. A random excitation results in random response dependent on the natural frequency of the product and the frequency range of the input vibration. Should the natural frequency be within the range and the duration of the input long enough, resonance will develop. Damage occurs as a direct result of vibration when a resonance condition concentrates high forces on fragile parts of the product. This force can be beyond the stress limit of the material and result in breakage. Also fatigue may occur which reduces the life of the element. Package resonance can quickly obscure labels and graphic design through abrasive contact within the cargo hold. In addition large compressive forces may be developed on package surfaces due to movement and the loading of product resulting in crushing of the package. Lateral force can be especially critical if the product is designed to only withstand vertical inputs.

III. VIBRATION MEASUREMENT

All engineering studies should be conducted in accordance with accepted experimental standards. Exact documentation of the project should be recorded to ensure the validity of the subsequent data. The investigation should be planned to proceed in a methodical manner. The information should be gathered carefully so that the data can be reproduced in future studies or refinements of a similar nature.

The aim in this case is to measure a vibration phenomena within stated objectives and parameters of the transportation environment. The number of modes available allow for many variations which should not be compounded to give a large overstatement of the subject. In a study the variables of the environment which are to be investigated should be clearly stated. These include type of vehicle and its structural characteristics, loading weight of vehicle, speed, and the run characteristics including surface type and operations. It is important to know all these parameters along with the basic methodology of the vibration measuring and recording system.

Since the two variables of vibration are magnitude and time, a device or devices will be needed to correctly measure and record them and their interaction. Earlier studies measured magnitude with a simple strain gage and plotted on a strip chart which moved at a specified rate. This combination, though not very responsive, gave an indication of the maximum amplitude and the duration of time.

Modern technology has greatly improved the accuracy of these measurements. Recent studies have been conducted using accelerometers which have high natural frequencies and are capable of very sensitive frequency measurements across the transportation range. These accelerometers are either piezoelectric or piezoresistive. Their output is electrical in direct proportion to the amount of internal distortion caused by the force input from the vibration.

The recording of the transducer's output has progressed both in quantity and quality with the use of magnetic tape. Tape recording provides an exact record of the vibration input response over long periods of time and allows this record to be thoroughly analyzed by different techniques at a later date.

In any engineering study the objective of the investigation and cost considerations affect the parameters, instrumentation, and depth of analysis. Based on the amount and quality of data desired a decision must be made on the basic components of the instrumentation system. The engineer must be aware of the possible problems and limitations involved and insure proper use and experimental design.

Accelerometers' frequencies vary from a very few cps to as high as 30 KHz. A high natural frequency will allow for a linear response over the anticipated vibration environment. A more critical point is the sensitivity rating of the accelerometer. DC response is necessary to be able to measure and distinguish very low levels of vibration. Care must be taken not to damage the accelerometer by an overload from a high input road shock or during installation. Secure installation is important because the mounting determines the response characteristics. Since vibration occurs in three planes, the accelerometers should be oriented for directional input normal to each plane. They should be able to withstand significant accelerations transverse to the sensitive axis, thereby giving a correct reading without any dissipation or additions.

There are many types of tape recorders available. The main features to consider are the number of channels available, sensitivity, range, and ease of use. The recorder must have DC response and a signla to noise ratio high enough to allow accurate resolution of the transmitted signals. This means correct coupling and cable type so as not to distort or lose data content. An accurate reading for analysis may be enhanced by use of low-pass filter within the input line to eliminate possible high frequency noise.

An additional piece of equipment, the amplifier, may be necessary to raise the recorded signal to a suitable level for analysis. It is important that this procedure does not distort the signal characteristics or introduce new problems such as noise. Again filters may be used to suppress unwanted signals which may interfer with the readings.

The correct output of a system requires that all the components be compatible so that the signal processed is not altered in any manner. It also depends on the proper isolation of the recording system, proper connections, and correct placement of the measuring devices so that data is not limited or eliminated. Usually this means having the recorder and required power sources in a separate compartment, either in the cab or an adjacent car. Placement of the individual accelerometers should be in the area most likely to receive rigorous input. Previous studies have shown that in some frequency ranges lateral forces are actually larger than the vertical forces. Accelerations in the front of a trailer may differ significantly from those recorded in the back. The question of the most severe location still remains open.

Another aspect of measuring the transportation environment is the actual moment of when to do so. There are many variable inputs which occur normally in transportation and many considered of a more uncommon nature. Selection of the relevant occurrences for study must be made. Since transportation vibration input is random there must be enough data to be able to be analyzed statistically. There are certain limitations as to the amount which can be continuously recorded. Objective judgement of the data must be made to determine the typical examples. Above all there must be consistency in selections for comparison. Before taping the requirements of the analyzing machines must be considered. Some instruments require long data segments but only use a small percentage of the actual data due to sampling techniques. Others can give almost instantaneous results utilizing all elements of a very short data interval.

IV. METHODS OF ANALYSIS

Transformation of the recorded data into hard copy requires instrumentation to read the signal, separate frequencies, and reduce the amount of the information to a useable size. The broader the scope of the study the more difficult it is to analyze because of the total amount of data available and the number of variables included. This will yield a broad range of measurements both continuous and transient. In contrast less conclusive and more exact measurements will be obtained from a project of limited scope. The choice of analyzing equipment is dependent on the objective of the study and must be considered during the initial phases of the project planning.

The two independent variables of time and amplitude must be given a measured value. A normal sine wave exhibits a variation in amplitude of an equal amount in both the positive and negative directions. This results in an average amplitude of zero. The most severe acceleration is designated the peak amplitude. This is the maximum height of the sine wave and occurs instantaneously twice per cycle. The average value of the sine wave is the average of a half-cycle or .636 of the peak. A more realistic value and the standard measure for electronic signals is the square root of the mean squared or RMS. The mean square value of a wave is the average of the sum of the squared individual magnitude differences from the mean value. In the case of a sine wave the RMS value is .707 of the peak value. Other wave shapes have different ratios of the RMS value to the peak value. If the data measured is Gaussian the RMS value and the standard deviation, σ, are identical. In general, the RMS gives the most statistically accurate account of the wave phenomena.

The time factor is easily converted into frequency but the problem is accurate presentation. The analyzing apparatus selected to examine the recorded data must be sensitive enough to pick up all frequencies and determine the differences in their magnitude. Filters play a critical part in this analysis process. A filter is an electronic instrument or network which allows certain frequencies to pass through to the next stage of analysis while blocking out all other unwanted frequencies. A filter may be high-pass or low-pass which allows frequencies over or under a specified point to be read or it may be a bandpass which will only pass those freuqencies within the bandwidth of the interval. The first two types are usually used in eliminating unwanted frequences for a clearer signal before analysis. The bandpass is used extensively in the actual wave analyzing process.

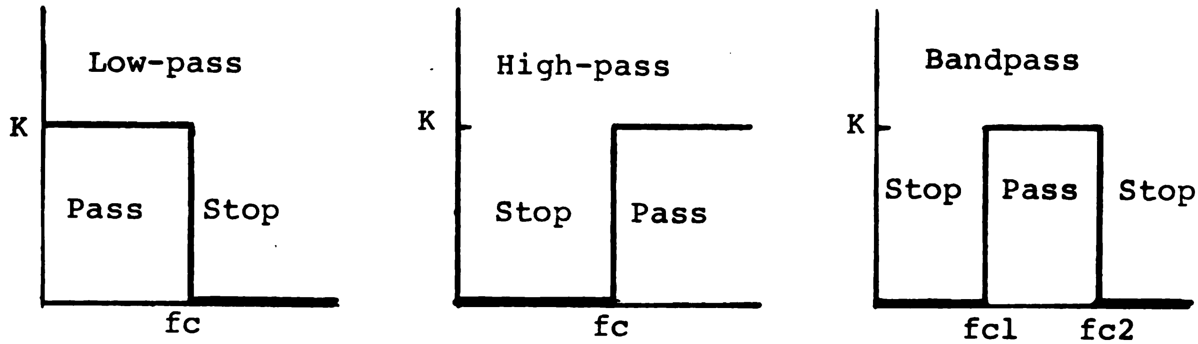

FIGURE 5.--Types of filters.

An ideal filter is one which would allow an exact number of cps to pass through at their full strength. The transmission characteristic would be unity. However, a real filter only passes a portion of the frequencies. The cut-off frequency of the filter is that frequency where the voltage gain drops to .707 of the passband value or -3db.

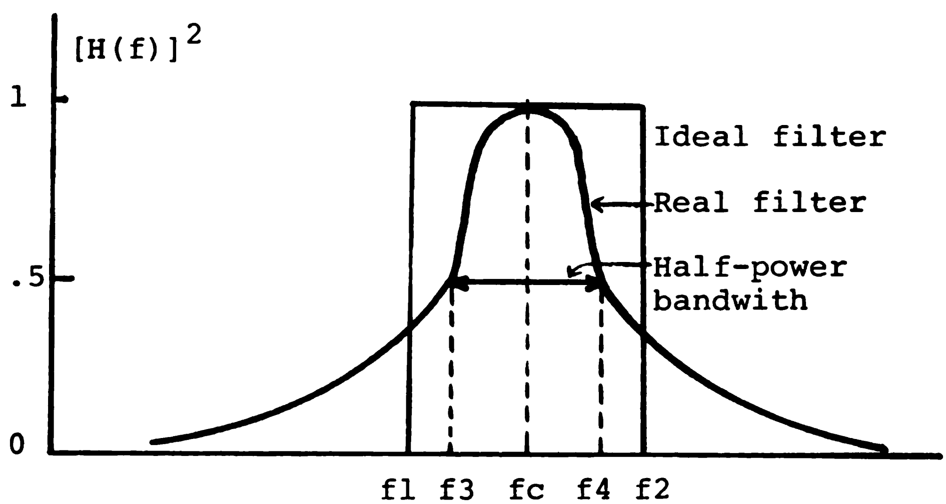

FIGURE 6.--Filter transmission characteristics.

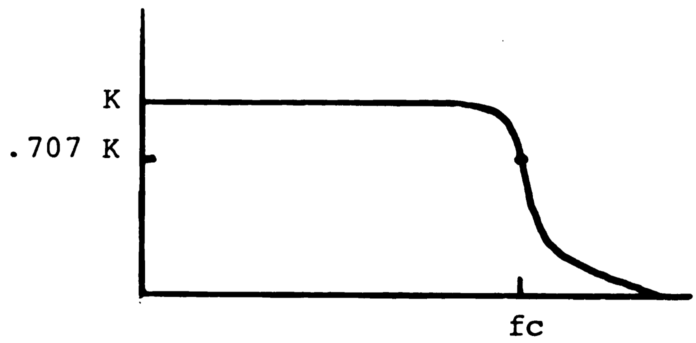

FIGURE 7.--Low-pass filter cutoff frequency.

The transmission characteristic is critical for small bandwidth filters. The value of a 1Hz increment is estimated by averaging the reading over the actual bandwidth of the filter used. This method will compound errors in reading very low frequency ranges. The size of a filter affects the time needed for the correct reading to be attained. This settling rate is another characteristic which has a direct effect on analysis time. The time required is usually equal to the reciprocal of the filter bandwidth.

Analysis may be performed using a number of machines which differ in accuracy, time requirements and type of value measured. The most elementary is the strip chart which translates the recorded or received signal into a graph of amplitude over time. The detected signal is proportionally displaced from the center line according to the magnitude of acceleration. The resolution of the time element is controlled by the speed of the chart. No frequency is indicated.

This visual representation is rather superficial but it gives an indication of relative values. It may help pinpoint areas of interest to be examined in greater detail. The limitation of the machine is the inherent slow mechanical response. This leads to individual amplitudes being superimposed resulting in misstated acceleration levels. Also this visual data record results in subjective judgements of what is a typical occurrence.

A more accurate representation of a wave is given by spectrum analysis. This is a determination of the power of a wave as a function of its component parts. A filter is used to scan the frequency range and the specific frequencies present are located. The wave is presented on an oscilloscope as the maximum amplitude input for each frequency. For instance a sine wave is presented as a single energy level at a single frequency. A composite wave of two different sine waves would be presented by two different lines. More complicated wave forms such as a square or sawtooth are presented as harmonics which are multiples of the principle or fundamental frequency.

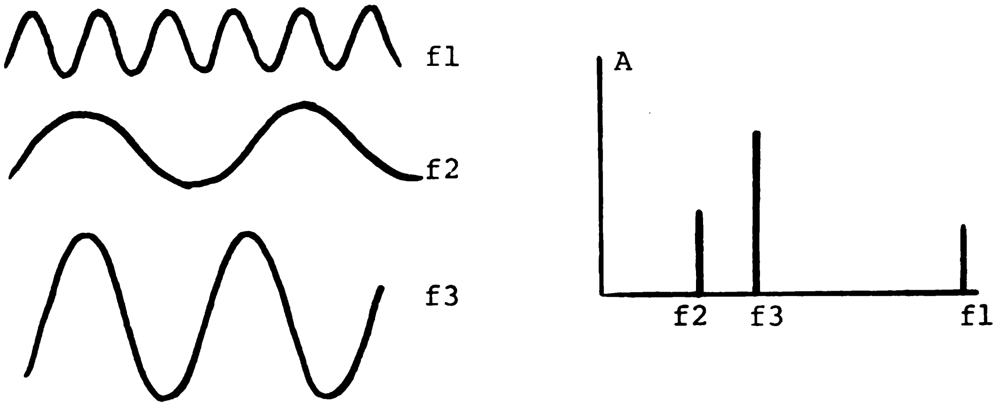

FIGURE 8.--Sinusoid spectra.

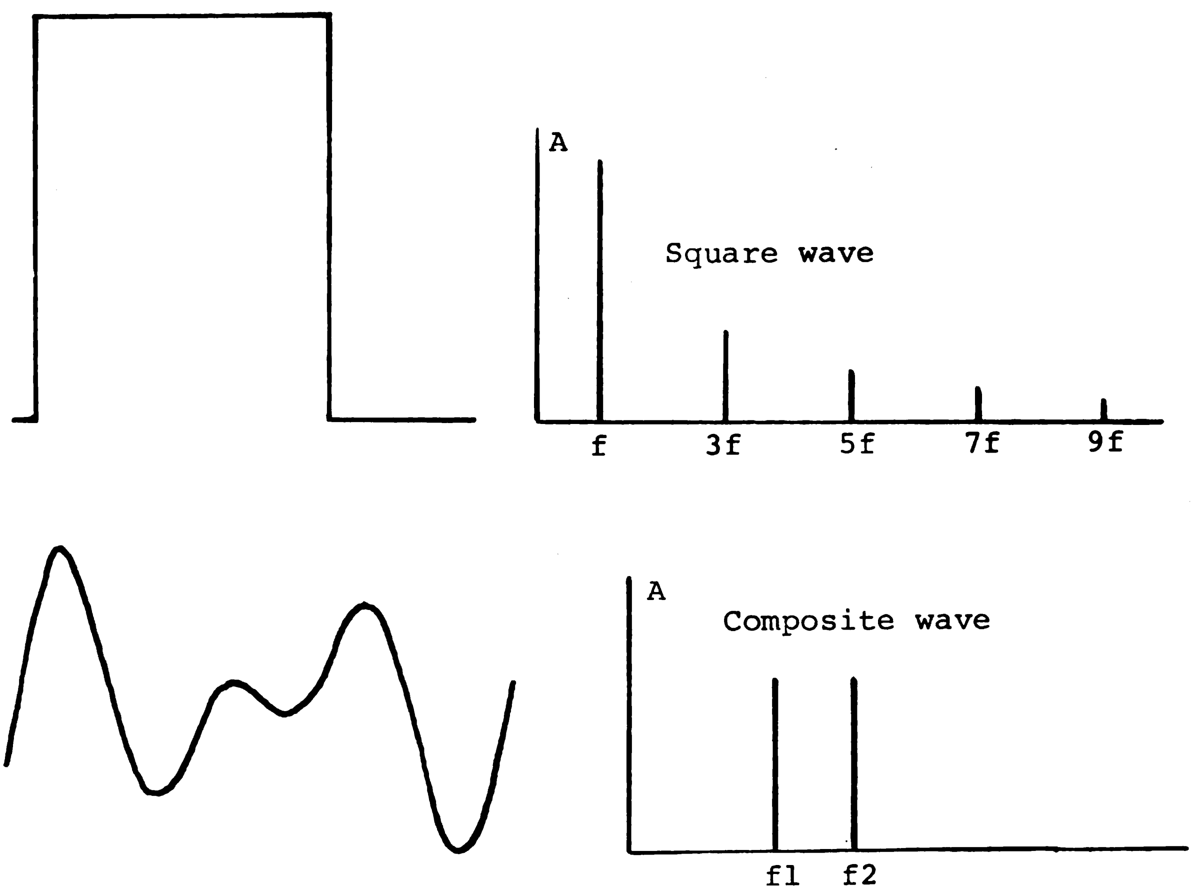

FIGURE 9.--Complex waveforms spectra.

For a random wave, which by definition is composed of various frequencies of varying amplitudes all changing over time, a wave analyzer is required. This instrument yields a visual output on an oscilloscope of the acceleration levels over all possible input frequencies. The wave analyzer determines the wave content by either sending the signal through a bank of filters of increasing bandwidth or by sweeping a single filter across the entire range. Records need to be quite long due to the settling time of the filters and the time required for sweeping. Although long data segments are necessary only 1% of the data might be used due to the sampling rate. An alternative method which may increase the chances of signal error is the use of a data loop. This would allow the same selected representative segment to be fully analyzed by repetition. A random wave would contain some measurement of all frequencies.

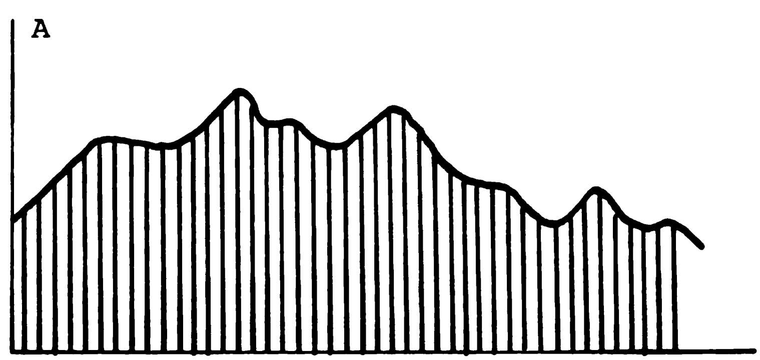

FIGURE 10.--Random wave spectrum.

Filters of course play a critical part in this instrumentation. Further information is required for complete understanding of their implications. The size or bandwidth of a filter determines the resolution of adjacent frequencies in the wave. For instance, two separate frequencies input to an analyzer may yield two entirely different wave shapes and amplitudes. The smaller the filter's bandwidth the more accuracy obtained. The superimposed waves will give an overstatement of the magnitude of the vibration condition. As seen in Figure 11, the amplitude measurement (11-d) is dependent on the filter's bandwidth (11a and 11b) and the spacing of the inputs (11-c).

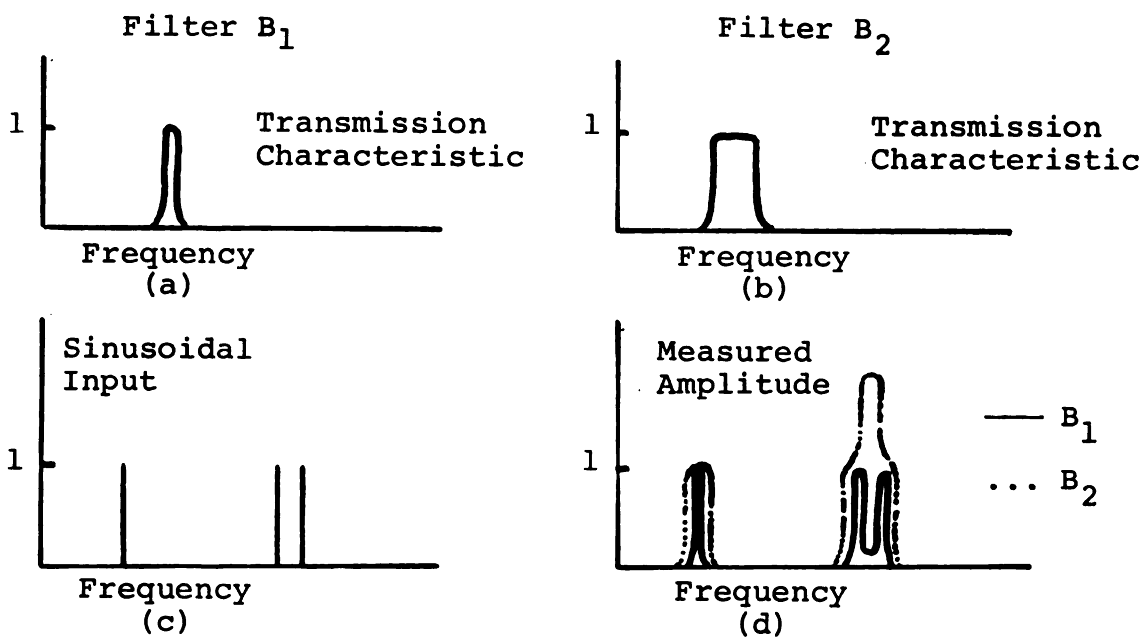

FIGURE 11.--Two filter transmissions.

Another aspect of wave resolution is the time requirement of the filter. A small single bandwidth filter used over the entire range will give fine resolution but requires an extremely long analysis time. Alternately the filters used may be of increasing bandwidth size which will smooth the measured input at the higher frequency intervals. Larger filters allow things to proceed at a faster rate. In addition large frequency ranges are generally presented on a logarithmic scale and fine resolution in the upper range is usually lost.

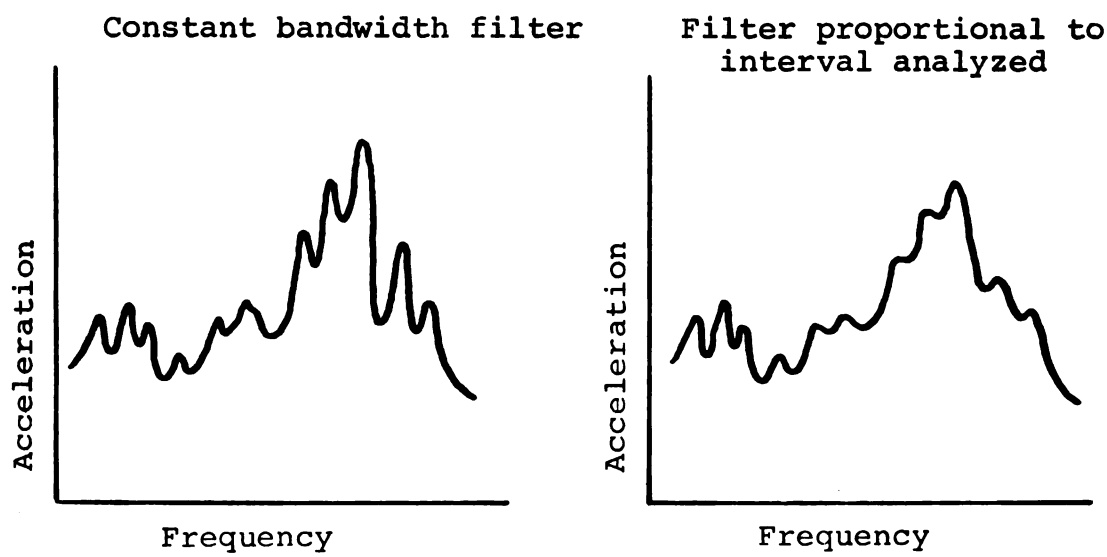

FIGURE 12.--Two filter resolutions.

The most sophisticated instrument available today for analyzing random vibration is the hybrid digital-analog realtime wave analyzer. This machine operates on the same principle as the wave analyzer. However, due to the computer memory it can read, average and present the information using 100% of the recorded data in a fraction of the previously required time. This is a result of a time compression memory which allows successive data samples to be immediately and continuously processed within the microseconds of the memory's operational time. The impact of using a 1500 word memory with a circulating period of .0001 sec. at a sampling rate of 30 Hz is that 50 s of data are in 100 μs of storage or a compression ratio of 500,000 to 1. A larger filter say of 10 KHz only requires 50 ms to sweep the entire spectrum and analyze it properly.

Since the vibration environment is a random phenomena it should be treated statistically. This requires stating values as a probability of occurrence. The realtime wave analyzer allows the retention of data so that the amplitude frequency occurrences over time or density can be computed. The value is most commonly known under the generic electrical phrase of power spectral density or PSD. Actually it represents the mean square acceleration density and the units are G^2/Hz. This measurement gives an indication of the extent of the dominant frequencies in a random input.

The output on the oscilloscope will be of a similar shape as that from the wave analyzer except for the units. A true random signal as exemplified by white noise measurements will have the same density across the entire range. Discrete input superimposed on a random signal or a narrow band random vibration input will result in peak occurrences. The character of the vibration signal is important to know for design purposes.

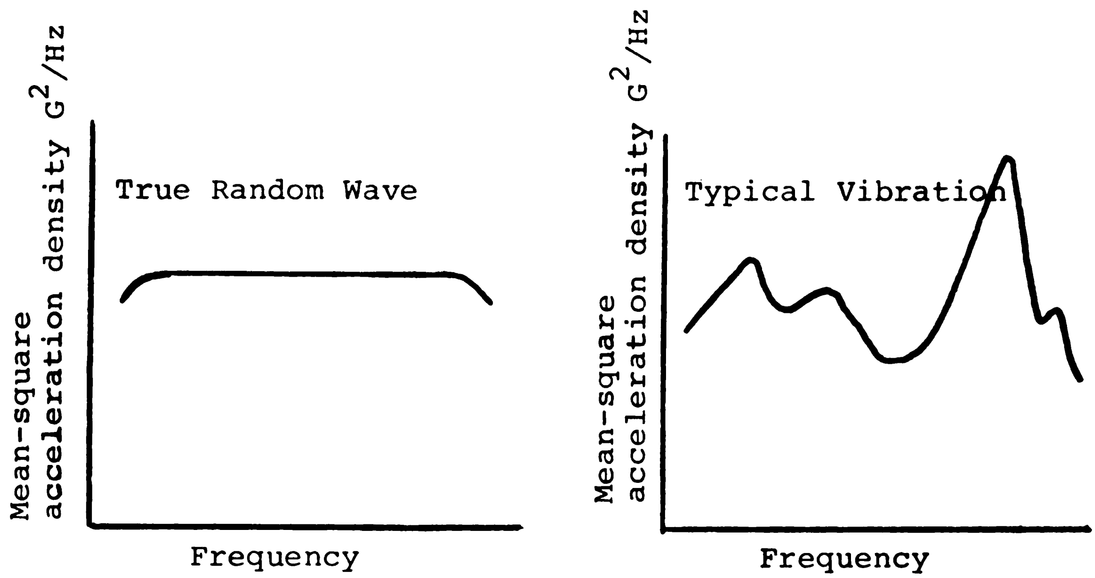

FIGURE 13.--PSD analysis.

Measurements taken from these analyzing machines can be utilized and presented in many ways. These will be examined in the next section.

V. DATA PRESENTATION

The presentation of the vibration measurements is determined by the inherent characteristics of vibration, the content determined by the method of data collection, and the intended use of the data. These three areas are interrelated and should be considered in the planning stages. The test design for the vibration study should be carefully planned so as not to include too much or exclude what is necessary. This will allow a quick and effective analysis. The important point of presenting any data is that it be correct and useful.

Since vibration is recorded as a measured displacement level over time, these two elements and their interrelationship are of primary interest. The frequency content of the vibration is important due to the natural frequency of any object. The acceleration levels are important in relation to the fragility level of the packaged product. The time history of the input to a vehicle is important for endurance stress considerations. The relative weight of each occurrence should be considered for its importance as an input to a specific system.

The objective of the study will set the parameters which will be included. These may include a study of the type of vehicle, effect of loading, speed, and road type. Initial objectives also set the data requirements. The test design will determine the level and extent of the measurements to be taken. The measuring method may limit the data recorded to peak amplitude or to preselected amplitude ranges. Analysis may be done for separate acceleration increments or averages. Intervals analyzed may be of varied length. This has a bearing on the accuracy, resolution, range, and completeness of the individual values presented.

The method of data presentation is dependent on the information which is required either for engineering calculations or test purposes. Definitive values for a specific variable studied may be presented with comparisons or a more general composite may be made. Engineering use may require more than one graph or table to apply to individual circumstances. Specific areas of interest include the maximum or average amplitude, specific frequencies, effect of test variables, and duration of input. Aside from the actual numbers or values of the elements their interaction and occurrence should be seen. This will result in some form of probability or statistical treatment. The common methods of presenting vibration data are discussed.

The most elementary presentation is the strip chart recording. It depicts the magnitude versus time history of the recorded vibration. No frequency can be read. This method allows the variation of possible levels to be seen. With this readout a typical segment may be isolated for more detailed study. The accuracy of the measurements is limited by the mechanical response of the moving needle and the chart speed.

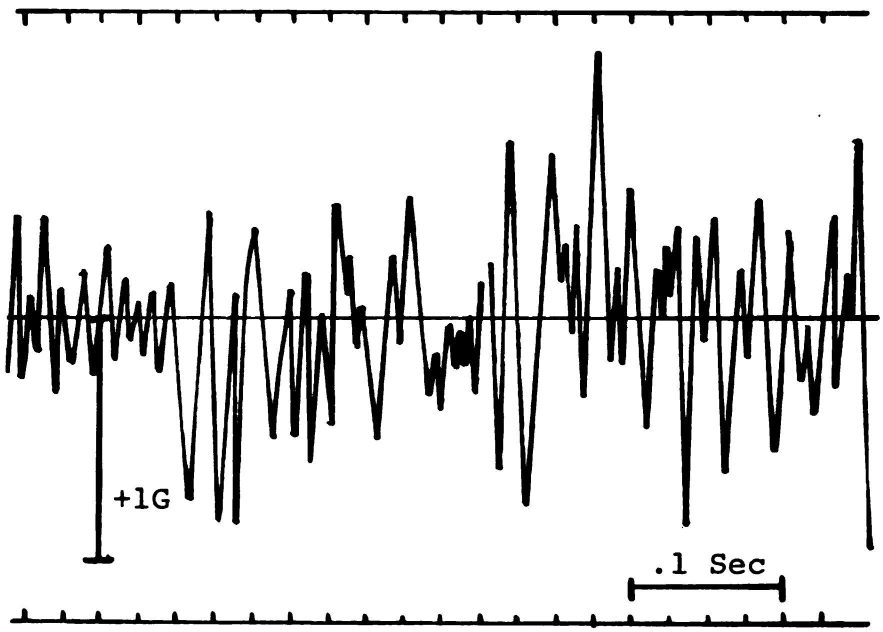

FIGURE 14.--Strip chart presentation.

One of the most common methods to show frequency is the envelop graph of acceleration levels versus frequency. This graph maps the maximum acceleration in G's that is attained within a measured frequency band against the center frequency of the band. The levels may be either peak or RMS. The individual points are then connected to envelop all frequencies across the range indicating their expected levels for that test situation.

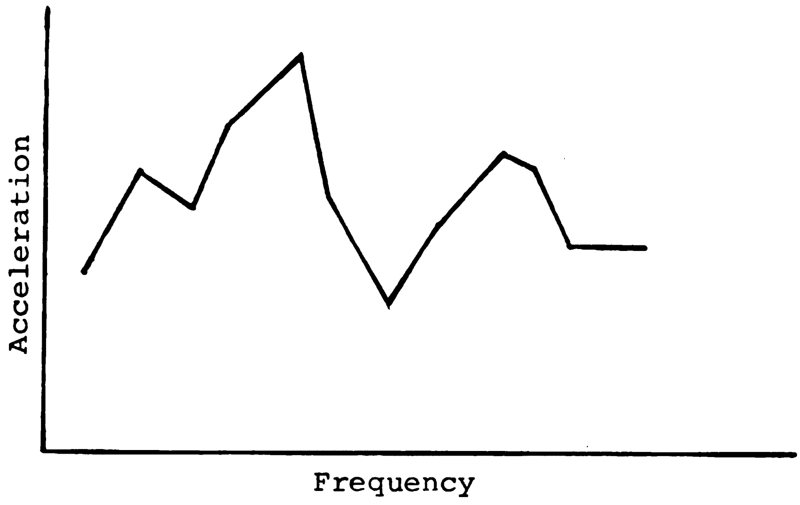

FIGURE 15.--Envelop presentation.

Individual graphs of different parameters such as measurement directions or speed may be superimposed to compare magnitudes and dominating frequencies. A possible problem is that an overstatement of levels may be made due to the size of the filter analysis or the inclusion of an occasional transient. Connecting the f_c of large analysis intervals may obscure dips in the range. Also indiscriminate combination of values from different conducted tests may result in errors due to differences in instrumentation, vehicle, road, and technique. The use of the envelope usually gives a very conservative picture of the environment.

A similar type of presentation is given by the bar graph. Here the maximum value attained in the measured frequency interval is presented for the entire interval.

Different measurement directions are often presented by different shading techniques. Again the size of the intervals are determined by the instrumentation and the amplitude resolution determined by accelerometer sensitivity and filtering.

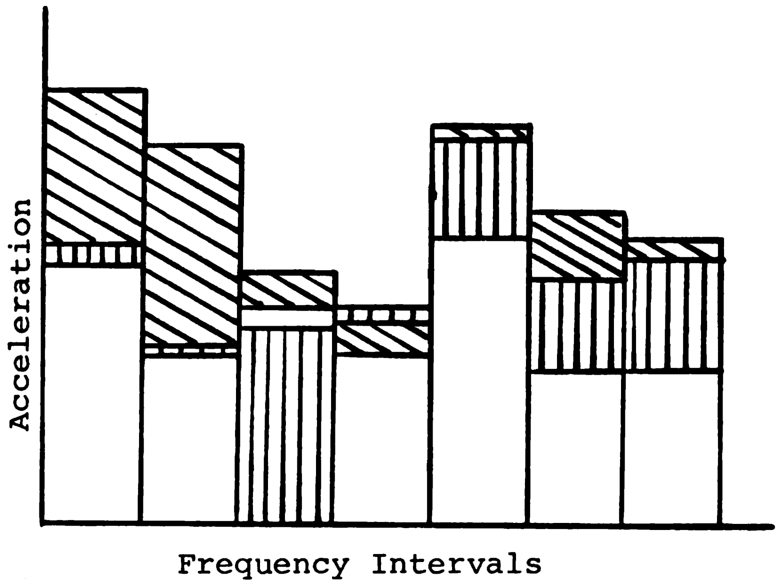

FIGURE 16.--Bar graph presentation.

A more exacting presentation is a numerical table which breaks out the percent of samples registered for each discrete amplitude level within each band interval. This is accomplished with the use of a computer which reads and sorts the signal. The visual table shows the relative occurrences in each acceleration level. This is more precise presentation but it does not allow for quick comparison of similar levels of different parameters or of similar percentages across the range. Transient occurrences are seen as a discrete jump a step above the previous level.

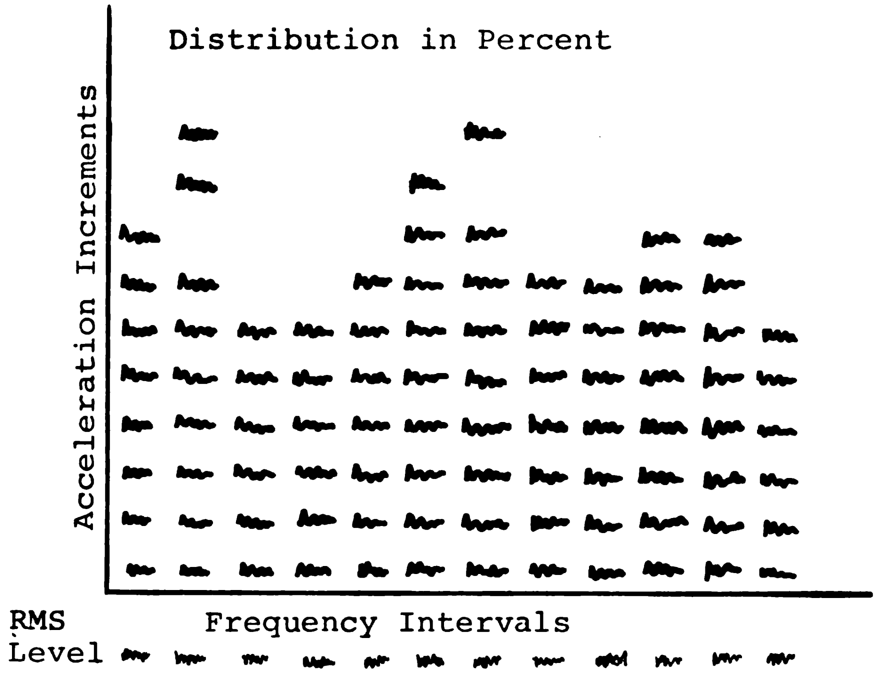

FIGURE 17.--Discrete figures presentation.

The VIBRAN diagram developed by Sandia eliminates some of the above problems. Probability levels are used in a plot of the expected magnitude against the center frequency of the measurement intervals. This graphic presentation of relative confidence levels allows quick analysis of the expected amplitudes. This method shows the large difference between the peak level and the levels registered for the major portion of the data. Comparison of different parameters may be made by overlaying their comparable probability levels.

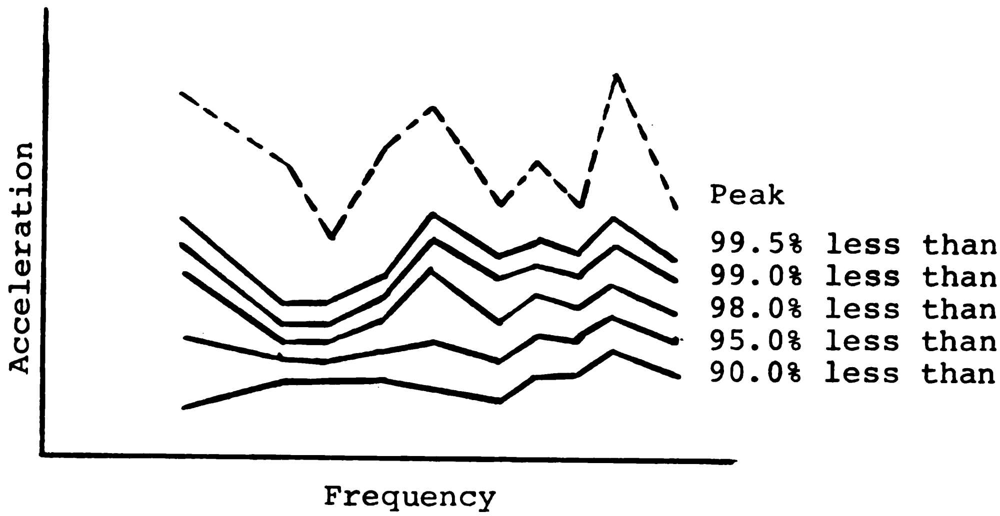

FIGURE 18.--VIBRAN presentation.

A plot of the PSD curves for a random wave input is obtained directly from the oscilloscope of a realtime wave analyzer. This graph will show the relative intensity of dominant frequencies across the analyzing range. The values may be read as either peak or average to be expected. The reading of mean square acceleration density for each frequency or G^2/Hz makes it difficult to convert to acceleration levels for comparison with other methods. An expected RMS level across the entire range may be computed from the area under the curve. The PSD curves may also be superimposed for comparison of parameters. This measurement is unsuitable for rapidly changing wave values. This type of measurements has the advantage of being extremely quick and not requiring a computer.

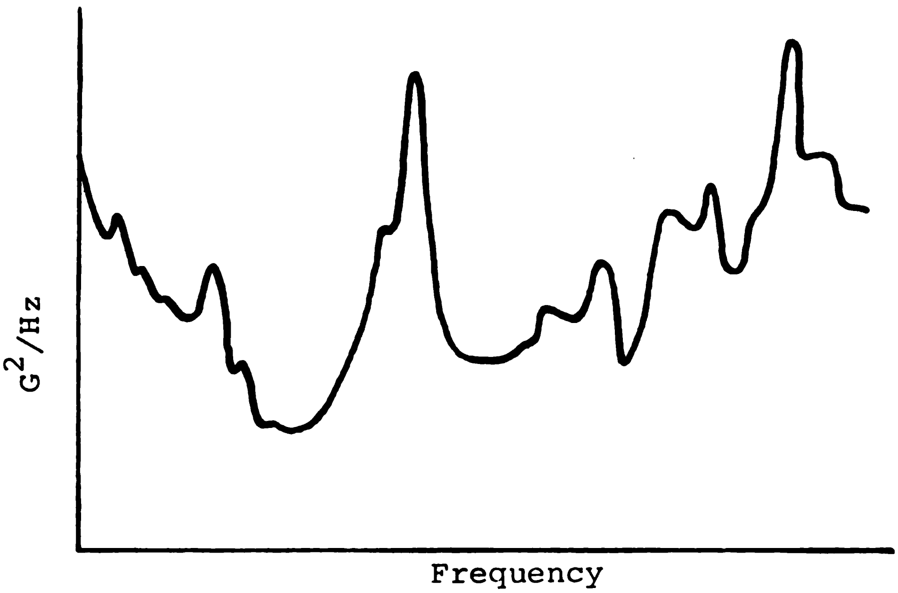

FIGURE 19.--PSD presentation.

All the above methods have been used to publish data on the vibration environment. However many problems and misunderstandings arise from a casual interpretation of the numbers. All studies and resulting values should be examined critically for the correct statement of range, sensitivity, technique of measurement, instrumentation employed, vehicles and other parameters. Variation in any one could significantly alter or obscure compared data.

VI. DISCUSSION

Although common vibration levels are known to be less than shock input levels, many problems still arise from the phenomena. These are due to interaction of the input frequencies, natural frequency of the product, and spring constant of the packaging material. A slight change in any part of the package or products distribution system may result in a damage situation eventually traced to vibration. For this reason adequate description of the vibration field is necessary.

A recent example of such a damage situation was highlighted in a trade magazine. A switch to a newer freight car caused fruit shipments to bruise. Closer examination revealed that the problem only occurred in the top containers. The cause of damage was attributed to the stiffer suspension which interacted with the corrugated containers' transmissibility factor. The input experienced at the top of the stacked containers was five times the original input. This problem was solved by use of a compressible foam inner pad which prevented attainment of the resonant condition through damping.

Another aspect of vibration damage was experienced in rail shipments of a photographic emulsion. Two liquids were packed in a plastic cartridge separated by a puncturable film divider. Vertical vibration testing according to accepted standards did not reveal any problems. However, initial shipments were ruined by premature mixing of fluids due to a breakdown of the divider's seal. Further investigation determined that the container was very susceptible to lateral vibrations which caused the fluid to impact against the plastic divider.

A third example of complications arising from vibration input occurred after the switch to palletized shipments. In this case product which had been block stored three pallets high with no crushing. When shipped by truck stacked two high the lower cartons were failing. The factors attributed were the dynamic load imposed by the upper pallet weight and the humidity weakening the corrugated.

These examples reveal the complexity and prevalency of the vibration problem. Every change in a system should be thoroughly examined for damage implications. New modes of travel may change input patterns. New transport designs are constantly being introduced for both specialized and general applications. Recent levels expected for rail have been close to one half the levels quoted twenty years ago. A transport design considered good for one packaged product may adversely affect another.

It is possible that the costly damage problems cited could have been completely avoided if complete attention had been given to the vibration implications. However, this area is often overlooked both from ignorance and the lack of decent information. All presentations purporting to define the vibration environment should be examined critically. Often the data is categorically stated as the level expected for all possible vibrations. However, one must consider carefully the test method and objectives. As stated previously an overstatement of the levels can be as costly as an understatement from the standpoint of package cost.

Unfortunately it is not always possible to establish the various components of a study. The chart which is presented often lacks an accompanying statement as to the instrumentation or methodology. A statement of the instruments measurement range is needed to explain the upper and lower cutoffs. The filter bandwidth used in analysis would indicate resolution and the amount of smoothing encountered by areas of rapidly changing acceleration. The type of measurement used for the acceleration levels should be stated. The difference between an average and the RMS signal may not be significant but for testing purposes or calculations it could be critical. The amount of noise in the system and the signal to noise ratio should also be stated.

A statement of the composition of the data should be made. As seen in the previous section transients may be present as indicated by the ommission of sampling points in an acceleration step of a frequency interval. This would increase unnecessarily the expected levels. The length of the recorded data may be important. Conditions of operation have a significant effect. Reports which are a composite of previous studies may be a composite of errors. Different equipment and methods used in each case may shift the graph of dominant frequencies or highest amplitudes. Composite reports usually combine diverse values since most smaller studies deal with noncommercial subjects and specialized vehicles. This is particularly true for air and ship studies which are concerned with structural dynamics instead of cargo.

Some graphic presentations give the impression that vibration increases indefinitely at the extreme ends of the ranges measured. While many studies concentrate on frequencies below 500 cps some have shown an increase of acceleration above those levels. All curves showing an increase in magnitude should be carried out until a leveling or down turn occurs due to damping of the system.

Special areas of analytical interest in vibration studies include transients, low frequencies, and the variation due to rotational inputs. In the analysis of rotating equipment for bearing failure spectrums are developed to measure abnormal frequency input and magnitude. To eliminate the difference in input due to the free coast down speed the successive spectrum readings are normalized. This means the frequencies are shifted in an amount determined by the ratio to the first order or base speed. It is possible that a similar shift may be observed in the vibration levels recorded at different speeds. This means a relative narrowband vibration input around the dominant frequencies of vehicle input would be found.

Low frequency acceleration levels quoted for the vibration spectrum are a problem. On many charts the lowest frequencies cited are among the highest in magnitude across the entire range. It is important that the levels be closely examined for the true extent of their impact. Some accelerometers do not adequately measure the low frequency ranges from 0-5 Hz. In Foley's report where the chart begins at 0 Hz he admits that his equipment did not measure below 2.5 Hz. This was not stated in the presentation.

Analysis of low frequencies requires good resolution so that the amplitudes are not superimposed. The fine resolution requires a very long analysis time due to the settling rate for the small filters used. The exact impact of low frequency input lies in the natural frequency of a product and the transmissibility of the package. Although typical fragility levels have been established for different product types it remains to be seen what are typical f_n of products. Bishop states that natural frequencies of whole structures are generally less that 50 Hz and rarely more than 500 Hz. This means that the excitation input of the transportation environment will have considerable effect.

Vibration is supposed to be a steady state input. Sandia reports that there is significant incidence of transients in the low frequencies. These higher levels are generally included in graphs as the normal steady state condition. These transients are not any higher than the steady state input of higher frequencies. More sensitive instruments may fill these apparent voids. Sampling rates may have had an effect on the percent of data examined and the probability that these points are indeed transients. As in shock evaluation the duration of these inputs is of the most importance.

Presentation of data in chart form is good for engineering requirements of design levels. It is important that the values be correct and inclusive of the anticipated environment. Levels and weight factors are needed for the development of vibration simulation tests. Tape input of an actual road test to a shaker would give an almost realistic input. This of course does not allow for interaction with the vehicle structure.

Previous reports present a certain amount of useful information. A survey of vibration measurements reveals a wide array of levels and relevant ranges.

With a solid background of expected levels, common measurement problems, and analysis techniques future reports can be of a more conclusive nature. New data is necessary because of the improvement in equipment and vehicles.

VII. REPORT COMPARISON

A review of literature defining the vibration environment shows that few studies have been compiled in recent years. In general, older studies were concerned with factors other than the environment experienced by cargo as it moves through the distribution system. Vibration analysis had been performed to measure the influence on the integrity of a vehicle's structure. Transportation vibration analysis has also been conducted with a variety of military vehicles or for specialized carrier applications. Due to the expense and time involved for a complete study few have been attempted and the full extent of vibration's affect on cargo has not been adequately defined.

Two of the most recently completed studies on the vibration encountered in common carriers were conducted by the School of Packaging. Separate reports examine the extent of vibration levels in freight cars and over-the-road trailers. The results of these reports are compared with the latest publication of the vibration environment as established in Sandia Laboratories Environmental Data Bank. These reports should represent the state of the art of engineering research on this subject. Pertinent information from other publications is also included.

This attempt at comparing vibration measurements has proven to be very complicated. Two areas of possible comparison are the methodology and actual values. As in any engineering study the objectives and parameters were established according to intended use and analysis method available. As a consequence the choice of equipment for sensitivity and the level of presentation may reduce the actual amount of information presented.

An account of the equipment, methods, and analysis instrumentation is necessary to compare the accuracy and extent of the findings. Parameters which should be examined include:

1. the frequency range and sensitivity of instruments
2. the use of filters in data analysis
3. the amount of actual data used in the analysis

Comparison of the actual data presented considerable problems. Although the basic elements of frequency and acceleration were the same the scales used were not the same. Problems encountered were:

1. different overall frequency ranges
2. different frequency intervals analyzed
3. different acceleration increments
4. different bandwidths filters used for resolution
5. the size of the sample and the number of averages employed

6. the statistical level of the presented data

For some of the presentations it is virtually impossible to manipulate the data to achieve a base for comparison. Some eliminate the very low frequencies due to the inherent difficulties in obtaining and analyzing them. Some do not carry out the analysis over a wide enough range due to the belief that the levels diminish or do not occur. The choice of the interval presented is dependent on indi-vididual analyzing and measuring techniques. A significant amount of overlap of intervals occurs in the different reports and it is impossible to break down the interval to individual frequency component levels. Use of standard deviation presentations present similar problems. Since the majority of occurrences of a frequency center around the mean level the higher the acceleration level the less number of events that will be occurring. For instance, 1% of the data may be responsible for 60% of the acceleration range. The distribution of the occurrences under the peak is not known and cannot be scaled down for a comparison.

The reports covered here will be individually summarized highlighting the significant findings and conclusions as drawn by the authors. A comparison of the reports will be made in a table for their significant factors and levels defined. Discrepancies in the given information and previously reported values will be noted.

Technical Report No. 20 published in November, 1972 was conducted to measure typical in-service rail vibration and analyze it using modern methods. Information concerning the equipment, methodology, and route factors were completely detailed. In general the vibration levels of a Hy Cube, 70 foot 100 ton box car were recorded on magnetic tape for three runs over the same track. The car contained 30 tons of scrap iron. The basic parameter changed was the springing of the suspension.

A continuous voice record monitored the variable events such as speed, crossings, and track type. Due to an over estimation of the vibration levels expected, the sensitivity of the recording system was set low. The result was a poor signal to noise ratio with an error in dominant peak readings of ±10% and larger for smaller levels. Analysis was conducted on segments of the data record where speed was held constant for a minute or more. These segments were selected from a strip chart read out of the RMS values. This selection method was used to establish both the transient and stationary periods of the runs chosen for analysis. These minimum stationary segments were required by the analyzer in order to allow proper settling time for the filtering function.

Wave analysis was not used due to the relative shortness of the record segments. The average RMS values were determined by a random noise voltmeter for all runs for speeds of 20, 30, and 45 mph over both welded and jointed track. Resulting ranges for these values were:

vertical	.079 to .312g
top lateral	.026 to .116g
bottom lateral	.022 to .129g

In general the measurements showed that the lateral directions were approximately the same while being three to ten times lower than the vertical accelerations.

PSD analysis of the stationary segments was done by a realtime wave analyzer to determine the frequency character of the data. This machine is capable of fairly good analysis of a very short signal depending on range. Due to the nature of the instrument's resolution, smaller intervals cannot be measured as closely over the short time. The maximum value obtained at the predominant peak at 60 Hz was .00082 G^2/Hz for a 0-500 Hz range. This measurement fell to .00038 G^2/Hz over a 0-200 Hz range. The computed RMS value for the PSD curves ranged from .15 to .38g. Other prominent peaks of lesser intensity were at 20, 40, 80, 120 and 400 Hz.

The PSD curves for lateral directions measured the top lateral value of .00015 G^2/Hz at 60 Hz over the 0-200 Hz range. The bottom lateral was .0003 G^2/Hz at the same point. Peak vibration intensity occurred at the same frequencies irregardless of springing which implies that there are resonances in the car and loading itself. An increase of speed raised all the PSD curves slightly but only shifted a single peak in the lateral direction. Welded rails scaled down the expected acceleration levels.

The extremely long data records required for high resolution of very low frequency data were unavailable. Instead spectral analysis was performed over the 0-20 Hz range. This revealed few predominant frequencies and the highest acceleration levels were very low compared to the average RMS measurements.

peak vertical	.035g at 3.6 Hz
peak lateral	.05g at .35 Hz

This was about the driving frequency of the rail joints. Other peaks though of a lower magnitude occurred at:

vertical	.2, .6, .9, 1.3 Hz
lateral	.5, .85, 1.0 Hz

A peak acceleration analysis for the 0-20 Hz range of the vertical data recorded the maximum value at .15g for 1 Hz.

An attempt at probability measurement was made through an interface with a digital computer. The data was found not to be a normal random distribution. The skewness was to be expected because although thought to be random from the large number of possible inputs, there are certain driving frequencies in the system. These will interact with load and speed variables to influence the dominant peaks recorded.

Analysis of the transient occurrences of rail crossings showed two different responses to the input. One was the gradual build up and subsequent gradual decline in acceleration levels across the time range. The second response was a large displacement then a slow return to normal levels. The maximum acceleration levels attained from these inputs were:

vertical	1.4g
lateral	.42g

Generally these shocks at crossing introduced accelerations of 1g vertical and 1/3g lateral above the normal state.

The authors conclude that more work is necessary to completely define the character of rail transportation vibration. The largest components of vertical vibration occurred at higher frequencies--60, 80, 120, 400 Hz--than originally expected. There were no predominant low frequencies. Presence of hydraulic snubbers was found to have a large effect on the vibration levels not the springing.

Technical Report No. 22 was published by the School of Packaging in September, 1973. The intent of the study was to obtain and analyze vibration data on common carrier trucks for use in package testing. Modern instrumentation was employed. The general setup was an array of piezoelectric and piezoresistive accelerometers placed in six spots in the trailer. The tape recorder and power source were placed in the cab and the data was monitored continuously. Three different trucks with three different loads were used over the same route. A fourth truck was recorded making local deliveries. Stationary segments of data for speeds 40, 50, 55 and 60 mph were used in analysis.

The RMS values were measured by a voltmeter with frequency response 2 to 20 KHz. The average range of acceleration levels were:

rear vertical	.33 to .68g
mid vertical	.15 to .34g
top lateral	.13 to .28g
bottom lateral	.13 to .30g

The front vertical measurement usually fell between the mid and rear levels. Comparison shows lateral measurements are smaller by a value of two or greater. Also the top lateral is usually rougher than the bottom lateral measurement. Lightly loaded trucks had a somewhat lower level of vibration independent of speed. Speed increased the level of vibration experienced.

PSD analysis was performed on the stationary segments of data. The predominant peaks for a curve with a .55g RMS level over 0-200 Hz are:

rear vertical	2×10^{-2} G^2/Hz at 3.75 Hz
	6×10^{-3} G^2/Hz at 15,25,70 Hz
	2×10^{-3} G^2/Hz at 140-200 Hz
top lateral	3×10^{-3} G^2/Hz at 7,15,20-25 Hz
bottom lateral	2×10^{-3} G^2/Hz at 15,25 Hz
	1×10^{-4} G^2/Hz at 7, 50 Hz

Greater resolution of the lower vertical peaks over a 0-50 Hz range changed some values:

2×10^{-2} G^2/Hz at 3.75 Hz
1×10^{-2} G^2/Hz at 15,25 Hz

Again the effect of speed was to raise the level of the PSD curve slightly while maintaining the peaks, although different peaks were more predominate at different speeds. Rear vertical and lateral curves look much the same while differing from those for forward and mid in frequency content. Heavy loaded runs exhibited larger peaks at 120 Hz. In general dominant frequencies are found from 0-50, 60-100 and 120-200 Hz.

Peak acceleration levels were computed by the real-time wave analyzer using 200 increments over 0-200 Hz range. The highest levels attained were:

rear vertical	.6g at 3.75 Hz
top lateral	.15g at 20 Hz

The rear vertical curve also showed prominent peaks of .45g at 70 Hz and .4g at 170 Hz.

Probability density was determined from a computer sampling of the signal at the rate of 500 samples per second. Sensitivity was 10 mv over a maximum peak to peak signal, 5 volts for a typical rear vertical signal. Results show a slightly skewed distribution of accelerations ranging from +2g to -2g. The standard deviation was .46g or in other words 68% of the data had less than that acceleration and 95% had less than .92g.

The VIBRAN graph was plotted to show the distribution of the vibration occurrences at each frequency. The highest g levels attained for the smaller intervals measured were .25g at 3.75 Hz and .55g at 150 Hz. The highest acceleration within the 95% confidence level was .1g across the entire range. When compared with the above standard deviation these figures reflect the effect of interval size on the total signal amplitude expected. Smaller intervals do not allow many superimposed amplitudes.

Analysis of transients was done using the real-time wave analyzer. The records for a one second segment can be adequately computed. This showed a large increase in low level frequencies above the steady state level and then a decay back to the steady state. Several transients from all runs were measured for the peak acceleration experienced. The following are the recorded ranges of transient inputs:

rear vertical	1.7 to 2.7g
top lateral	.7 to 2.0g
bottom lateral	.3 to 1.1g

Separate analysis of the local peddle run determined the peak transient values attained to be from .3 to 1g with a more uniform distribution of peaks. Few low frequencies predominated. This might have been the direct result of a small 30' trailer with a very light load. These values are well within the range of the over-the-road transients.

The authors conclude that present standardized tests are not representative of the dynamic environment as indicated in the report. They advocate a test based on a composite PSD plot which states more information than other plot forms. Transients show a gradual increase in level and could be included within the steady state tests.

The third article reviewed was used as a comparison base. "Current Predictive Models of the Dynamic Environment of Transportation" by J.T. Foley was published in

TABLE 1.--MSU-Reported Values.

	#20 - RAIL	#22 - TRUCK
RMS Range (2-10K)	vert. .079 - .312g t. lat. .026 - .116g b. lat. .022 - .129g	r. vert. .33 - .68g m. vert. .15 - .34g t. lat. .13 - .28g b. lat. .13 - .30g
PSD G^2/Hz max peaks	Verticals 8.2×10^{-4} at 60 Hz (0-500) 3.8×10^{-4} at 60 Hz (0-200) Laterals t. 1.5×10^{-3} at 60 Hz (0-200) b. $.3 \times 10^{-4}$ at 60 Hz (0-200) Other Peaks 20,40,80,120,400 Calculated RMS .15-.38g	Verticals 2×10^{-2} at 3.75 Hz (0-200) 6×10^{-3} at 15,25,70 Hz (0-200) 1×10^{-2} at 15,25 Hz (0-200) Laterals t. 3×10^{-3} at 7, 15, 25 Hz (0-200) b. 2×10^{-3} at 15,25 Hz (0-200) 1×10^{-4} at 7, 50 Hz (0-200) Other Peaks 0-50,60-100,120-200
Probability	σ = .106g range = +.75g to -1.1g	σ = .46g range = +2g to -2g
Low Frequency Analysis (0-20)	Vertical .035g at 3.6 Hz Lateral .05g at .35 Hz Peak Measurement vert. .15g at 9 Hz	
Peak Measurement (0-200)		Vertical .6g at 3.75 Hz .45g at 70 Hz .4g at 150 Hz Lateral .15g at 20 Hz
Transients Range max. values	vertical .95 - 1.42g t. lateral .14 - .40g b. lateral .24 - .42g	vertical 1.7 - 2.7g t. lateral .7 - 2.0g b. lateral .3 - 1.1g

TABLE 2.--List of Variables and Instrumentation.

STUDY	MSU #20	MSU #22
Objective	in-service rail conditions	commercial truck shipments
Scope	different spring rates	different load weights different trucks
Vehicle	Hy Cube 70 ton 100' boxcar	semi-trailers 30',40',45' lengths
Road Type	well traveled main trunkline	state highway local city road
Accelerometer	range 0-1g sensitivity 6.25 mv/g	range 0-1g and 0-10g, sensitivity 100 mv/g and 10 mv/g
Acc. position	vertical top and bottom lateral	4 vertical top and bottom lateral
Time	continuous record 1 hour cassettes	continuous record 1 hour cassettes
Recorder	100 mv max. input DC-400 Hz	100 mv max. DC-400 Hz
Reproducer	1v max. output 100 mv/g	1 RMS max.
Amplifier	100 x gain	until max. signal 5v peak to peak
Filter	variable .02 Hz bandpass	.1 to 500 Hz bandpass
Voltmeter	range: 2-10 KHz	range: 2-10 KHz
Wave Analyzer	DC-1 MHz 1/400 resolution	DC-1 MHz 1/500 resolution

The Journal of Environmental Sciences for January/February 1973. This report was a combination of selected tests and previous studies run by the Environmental Criteria Group at Sandia Laboratories. The fact that the same group did all the measurements provides for a certain amount of continuity in data reduction and presentation.

Two types of graphs are presented for each mode of transportation. Where enough detailed data was available to complete a statistically reliable presentation, a distributive model was given. This method attempted to use only Gaussia random data by first removing any discrete frequencies within. A bar chart of 1σ or 68% of the data was presented as continuous broadband excitation. An envelop model was used to display peak accelerations obtained for the various transient phenomena. While the envelop model gives the maximum value obtained and is overly conservative, the distributive model provides a degree of risk in accepting the established levels.

Truck information was summarized over a 10-1200 Hz frequency range for the continuous data and 0-100 Hz range for the discrete transient data. Information was used from seven different truck studies. The range of continuous accelerations recorded were:

vertical	.13 - .6g
lateral	.04 - .4g
longitudinal	.08 - .5g

The lateral data is actually lower than both vertical and longitudinal. There was not a PSD presentation given to determine the frequency content. Predominant frequencies were estimated from the center frequency of the bar interval with the highest acceleration value. Based on this approximation the values were:

vertical	15 Hz
lateral	60 Hz
longitudinal	110 Hz

Peak transient accelerations as measured over the 1-100 Hz range were:

vertical	10g at 3.75 Hz and 10 Hz
lateral	1.2g at 30 Hz
longitudinal	1.2g at 15 Hz

Foley states that the major sources of excitation input for a truck depending on speed are:

suspension system	3 - 6 Hz
tires	15 - 25 Hz
drive train	60 - 80 Hz
frame	100 -120 Hz

Comparison will show that these frequencies do dominate.

Rail transport was summarized over a 10-350 Hz frequency range for a 1σ distribution model and 1-100 Hz range for the enveloped transient model. Information was used from 22 different events. Foley states that data was only available to 350 Hz and claims that the accelerations had leveled off by that point. The range of continuous accelerations recorded were:

vertical	.03 - .1g
lateral	.023 - .055g
longitudinal	.018 - .055g

Predominant frequencies were again estimated from the center frequency of the bar interval. The results are:

vertical	30 Hz
lateral	100 Hz
longitudinal	60 Hz

Peak transient occurrences not including switching were:

vertical	4.5g at 70 Hz and 3.75 Hz
lateral	5g at 30 Hz
longitudinal	5g at 30 Hz

Comparison with the major frequencies as stated by Foley for rail vehicles again shows some relationship:

suspension system	5 - 10 Hz
frame	60 - 100 Hz
track input	10 - 30 Hz

TABLE 3.--Foley Reported Values.

	Foley - RAIL	Foley - TRUCK
RMS Range	(0-350) vert. .03 -.1g lat. .023 -.055g long. .018 -.055g	(10-1200) vert. .13 - .6g lat. .04 - .4g long. .08 - .5g
Predominant Frequencies	vertical 30 Hz lateral 100 Hz longitudinal 60 Hz	vertical 15 Hz lateral 60 & 1100 Hz longitudinal 110 & 1000 Hz
Transients	(0-100) vert. 4.5g at 70 Hz lat. 5.0g at 3.75 & 30 Hz long. 5.0g at 30 Hz	(1-100) vert. 10g at 3.75, 10 & 1100 Hz lat. 1.25g at 30 Hz long. 1.2g at 3.75 & 15 Hz

Another study conducted in 1970 for Sandia by Gens is used in conjunction with Foley's report. It covers the vibration experienced by a flat car and the apparent weight of its cargo. This study was presented as a detailed table of the VIBRAN program. Approximate 1σ levels were extracted for inclusion with Foley's values. Predominant frequencies were again centered within presented interval and were compared with Foley's results. Individual levels are not discussed here but are presented in Table 4.

Deciding which values to compare among the varied presentations was difficult to do. A straight forward comparison of acceleration levels necessitated having the same level of probability of occurrence. Foley's 1σ levels were taken to be nearly equivalent to MSU's RMS levels according to statistical theory and sinusoid measurement. The values for different vibration directions such as mid and aft verticals and top and bottom laterals were combined to make one value range for comparison.

A more difficult problem was the ranges presented which do affect the values for acceleration levels and frequencies. Due to the number of driving frequencies and structural frequencies present in the vehicle, more than one frequency may be of an equal intensity across the spectrum. Indeed a true random situation would exhibit equal values. Division at a driving frequency leaves a decision as to its real value. The accuracy of the two groups' data methods

TABLE 4.—Miscellaneous Reports.

GENS	GUINS	LUEBKE	FOLEY '69	OSTREM '72
R.R. Flatcar	R.R. Boxcar	R.R.	Truck Conds.	Truck
RMS				
vert. .12 - .43g	STEADY STATE	PDS	NORMAL OPS	RMS (1-1000)
lat. .06 - .15g	.25 - .5g	8.5 x 10^{-4} at 5 & 70 Hz	RANGE (0-350)	vert. $<$ .1g
long. .07 - .23g			.1 - 1.65g	
	TRANSIENTS	MAX		PEAKS
VIBRAN	.5 - .8g	3g	ABNORMAL OPS	vert. 10 & 100 Hz
vert. 30-45 Hz			.86 - .11g	
lat. 60-125 Hz	DOM. FREQUENCIES	RMS RANGE (0-700)		PEAK READINGS
long. 30-45 Hz	2.5 - 7.5 Hz	.03 - .3g	PEAKS	vert. 3g at 100^{+}Hz
175-25 Hz	55 to 65 Hz		175 - 250 Hz	
CALCULATED RMS				
.37 - .79g				Rail
PEAKS				RMS (0-1000)
				vert. .1g
vert. 1g at 2.5 Hz				lat. .035g
lat. .52g at 100 Hz				long. .02g
long. .52g at 200 Hz				
				PEAK READINGS
				vert. 1g at 7 Hz
				lat. .5g at 120 Hz
				long. .5g at 120 Hz

and instrumentation could not be compared since Foley did not explain his in the magazine.

Since Foley's report is a composite of different individual studies, it would be expected to have a wider, more extreme range of values. This is verified. Likewise, since trucking encounters a more diverse road bed and input, these vibration levels would be expected, and are larger than those experienced for rail transport. The relevant figures are summarized in Table 5.

Rail vibration levels measured by MSU fall within the range established by Sandia. The frequency values are somewhat the same. A problem occurs where the cut off frequency of the interval is the predominant frequency in PSD analysis. These predominant frequencies are higher than those recorded by Guins in 1953 of 2.5-7.5 Hz and 55-60 Hz. Detailed low frequencies analysis over 0-20 Hz presented by MSU reveal very low accelerations:

vertical	.035g at 3.6 Hz
lateral	.05 g at .35, 1.2 and 9 Hz

compared with the .2g to .5g given in Guins report. This may be as a direct result of improvement in rail cars and the data collection and analysis.

One other source for comparison was a report presented by Luebke. He suggests the rail environment has dominant frequencies at 5 Hz and 70 Hz with a range of .03 - .3g. This is close to the MSU figures.

TABLE 5.—Report Comparisons.

		RAIL		TRUCK	
		MSU	Foley & Gens	MSU	Foley & Gens
RMS RANGE	vertical	.079 - .312g	.03 - .43g	.15 - .68g	.13 - .6g
	lateral	.022 - .129g	.023 - .15g	.13 - .30g	.04 - .4g
	longitudinal	------	.018 - .23g	------	.08 - .5g
DOMINANT FREQUENCIES	vertical	20,40,60,80,120,400 Hz	30 Hz	3,75,15,70 Hz	15 Hz
	lateral	60 Hz	60,100 Hz	7,15,25,50 Hz	60 Hz
	longitudinal	------	60,200 Hz	------	110 Hz
PEAK READINGS	vertical		1g at 2.5 Hz	.6g at 3.75 Hz	
	lateral		.52g at 100 Hz	.15g at 20 Hz	
	longitudinal		.52g at 200 Hz	------	
TRANSIENTS	vertical	1.42g	4.5g at 70 Hz	2.7g	10g at 70 Hz
	lateral	.42g	5.0 at 30 & 3.75 Hz	2.0g	1.2g at 30 Hz
	longitudinal	------	5.0g at 30 Hz	------	1.2g at 30 Hz

Transients measured were much higher in Foley's report though still at dominant frequencies. The transverse values are almost the same as the vertical values.

Truck vibration levels measured by MSU were almost the same as those of Sandia. Foley used a wider analysis range so that those values could be expected to be higher. He also reports that the values for the longitudinal direction exceeded those for the transverse direction. In general any of the directions can record the highest level within some part of the spectrum. The predominant frequencies in the truck environment are lower than those for rail. There is considerable activity between 0 Hz and 25 Hz. The transients experienced are larger than those recorded for rail.

VIII. CONCLUSIONS

The preceeding examination of vibration and its measurement in transportation environment still leaves considerable room for improvement. Until certain standards are formed this area will remain an unwieldly conglomeration of data. Vibration measurement, analysis, and presentation should be done in an orderly and useful manner. Indiscriminate use of numbers or unsatisfactory equipment cause a misrepresentation of the phenomena as experienced by an actual shipment. Many areas remain to be tackled in extensive studies to give a more complete picture of the real environment.

Orderly and exact collection techniques are the responsibility of the researcher. It is also his responsibility to state the objectives and methods used when the figures are presented. This will allow others to know what has been done and allow a possible comparison. Statements of omissions or mistakes are just as important for understanding.

Presentation of vibration data should be in a useful and realistic form. Since the transportation environment is a random phenomena, probability theory should be incorporated to establish the chance of occurrence. Units used for description should be easily understood and useable for comparisons. Accurate conversion for inclusion in mathematical calculations is necessary.

The engineer must have an adequate base of information about the amplitudes and frequencies expected. Information on cushioning and natural frequencies is needed to develop the resultant input to the product due to package interaction. A useful chart is one which will allow these values to be extracted for use in package design. A package should be able to withstand the input, maintaining its function of protection and marketability throughout the distribution phase. The decision of the extent of vibration protection will involve a trade-off between package costs and cost of possible loss from damage.

The most conservative presentation design for a mode is the composite envelop method covering the peak amplitudes across the fullest possible array of variable parameters. When comparing these the truck vibration environment seems to be the most severe excluding the rail switching impacts and airline's high frequencies. This form would seem to be the single most useful presentation since virtually all product travels by truck some of the time.

The most statistically useful presentation from the standpoint of the magnitude of input is the VIBRAN format. Comparison of the different levels of occurrence in a particular environment allows an option for a greater degree of risk in lower protection levels as a cost consideration.

The method which yields the best frequency information is the PSD curve. It shows the dominant frequencies and has the average RMS acceleration level of the curve as measured by the area under the curve. Use of the real-time wave analyzer requires considerably less time and cost than the computer program VIBRAN. This method is better because of the continuous uninterrupted analysis across the range which does not cause measurement problems at the interval cuts.

As is generally the case, one chart cannot adequately define the information required for the vibration experienced. Combining innumerable variables will make it very difficult to confidently generalize because there will always be exceptions. One reason for the definition of vibration input is to have realistic values for use in developing an ideal package for any product. Analysis of the package and the product reaction to the input is important. This analysis can be conducted more economically in lab simulation than in test shipments.

The second reason is a compilation of charts which represent the entire vibration field and all its variables is necessary for definition of test limits. Current methods for testing packages are inadequate and incomplete. Vibration tests are conducted to simulate the environment.

ASTM specifies a continuous one inch amplitude input to a mechanical shaker which is a very large input for most packages. The test is customarily conducted for one hour. The result of this test method is acceleration in excess of 1g and either immediate failure or none at all.

Test equipment is becoming more sophisticated. Exact input for frequency, amplitude, and force may be closely regulated to approximate levels of the environment. Vibration measurement is required to establish exact inputs for simulation. Current controversy is over the constant force input or constant amplitude input. Frequency may be taken care of by a suitable sweep time which would allow enough time for product to react. Established driving frequencies could be singled out for a longer dwell time. New vibration standards should be of general nature to allow for both large and small product and different types of equipment. Of course each engineer can set more rigorous limits in line with his product, distribution system, and test machine.

Other subjects which were previously mentioned in earlier sections would be of further interest for clarification and definition of the vibration environment. These areas are necessary in defining the vibration limits and repercussions so that all calculations would be done with assurance.

A set of standards is needed for the measurement of vibration. Previous studies have shown a tremendous variation in technique. For a detailed investigation instrumentation ranges, placement, and time requirements should be specified to allow more exacting compilation and comparison. The specific parameters such as vehicle load, road type, and operations should be exactly stated. Measurement of the vibration effect on cargo in ships and planes needs to be done and these must also have placement specifications.

Of more immediate concern is clarification of the complex vibration experienced in piggyback and other containerized shipments. Palletized shipments should be examined to trace the effect of added weight and the dynamics of stacking.

A more precise measurement of driving frequencies and structure of vehicles is needed. Present statements on the subject cover a significant range. The calculation could be made to show the effect of speed and load variables.

A study of the typical natural frequencies of various products would be informative. Fragility factors for shock endurance have already received much attention from both a how to define standpoint and common values for different product types. A knowledge of the natural frequency of a product and its interaction with various cushioning materials would allow accurate designs.

Cushion materials should have curves relating natural frequency to the static loading for different cushion depths. Also a statement of the expected transmissibility curves for the cushions. The vibration input from stacking arrangements is important.

Low frequency should be more clearly resolved to determine exact magnitudes and the occurrence of transients in this area. Their implication for design in relation to typical natural frequencies and amplification factors should be carefully examined to see if this area is really critical in relation to its high cost of analysis.

Other aspects of environment affecting vibration levels should also be examined. The effect of temperature on the natural frequency of cushioning materials and the effect of humidity on the strength and transmissibility of corrugated containers is critical. The amount of dynamic stress able to be handled by these package materials in adverse conditions should be plotted.

Knowledge of these factors would allow a more realistic evaluation of transportation surveys. All shipments of product which sustain damage should be carefully examined for unusual circumstances before redesign. Interaction of these other factors may influence the amplitude or dominant frequencies registered for a specific incident.

In conclusion, the importance of the transportation vibration environment in packaging must be stressed.

Although the g levels are not as high as those for shock input from rough handling, the result of a steady state input can be just as devastating. The exact damage value attributed to vibration is unknown. However, as shown by the examples vibration does cause considerable problems. Any change in product, transportation mode or package design should be suspect and checked out for possible repercussions. Proper understanding and emphasis is essential for eliminating this type of damage. The engineer needs realistic and clearly defined input information in order to thoroughly design the package.

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