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TRUCK CAB VIBRATIONS AND HIGHWAY SAFETY

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16. Abstract

Exposure to vibration of drivers of trucks and tractor-trailers has often been implicated as a negative influence on driver health and highway safety. This document reports the findings of a research project in which the state-of-knowledge on the links between the truck ride vibration environment and accident involvement was critically reviewed by a panel of experts in an effort to evaluate its significance as a public safety issue.

The state-of-knowledge linking the truck vibration environment to effects on driver performance, and ultimately accident involvement, is insufficient to provide direct evidence of the significance at this time. Experimental data obtained in this project demonstrate that truck vibration level is related to road roughness from which it may be inferred that the vibration levels will increase in the future if the highway system continues to deteriorate.

The panel of experts recommends the continuation of research in the area of truck ride vibration and its effects on driver performance, and in the area of road roughness as it affects ride, safety, and roadway deterioration.

This report consists of two volumes:

Volume I - Summary Report; Volume II - Technical Report with Appendices

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This report documents a research program performed for the Federal Highway Administration examining the relationship between truck vibration and highway safety. The research involved experimental measurements of truck vibrations, a state-of-the-knowledge review of the vibration/safety relationship, and the conduct of a conference to explore the consensus among experts on the topic.

The authors wish to thank Messrs. Michaël Sayers, John Campbell, and Don Foster for their help in the collection and analysis of experimental data.

The State-of-Knowledge Review on the Relationship of Truck Ride Vibration to Highway Safety (Section 2.0 of this report) involved broad areas and disciplines. Many people on the HSRI staff contributed to its writing, both in the preliminary form and as reflected in this report. Professor Leonard Segel authored the introductory section; Dr. Thomas D. Gillespie, the section describing the truck ride environment. Dr. Lawrence Schneider prepared the section elaborating the effects of vibration on man, with the able assistance of HSRI staff members—Melissa Pflug, Dr. Robert Matteson, and Cynthia Donahey. The last section, examining the evidence to relate vibration exposure to accident frequency, was prepared by Dr. Kenneth Campbell with assistance from Dr. Oliver Carsten. Throughout the endeavor, the staff received able assistance from Kris Huber of the HSRI Library in identifying and obtaining the relevant literature.

In preparation for the Conference, Dr. Ronald Lippett, Professor Emeritus at The University of Michigan, and his associate Kathleen D. Dannemiller, provided the advice and concepts from which the conference design was selected. Ms. Jeannette Nafe attended to the myriad of administrative details essential to its conduct. Finally, the conference participants, as identified in Appendix A, deserve recognition for their professional dedication, as reflected in their contributions to the conference and their many helpful suggestions for improving the State-of-Knowledge Review.

1.0 INTRODUCTION

1.1 Introductory Remarks

This report documents a study sponsored by the Federal Highway Administration (FHWA) and conducted over the period of July 1, 1981 through February 1982. The project was conceived out of need to provide governmental decision makers with guidance on the urgency of truck vibration as a societal issue merting federal involvement.

In the mid-1970's, the vibration exposure of drivers of commercial trucks was raised as an issue to the federal government—namely, do vibrations (as well as noise, toxic fumes, and other factors that contribute to truck "ride quality") have a negative effect on driver health and on highway safety. The responsible federal agencies, including the Federal Highway Administration and the National Highway Traffic Safety Administration, pooled their resources in a coordinated program addressing the issue. The FHWA took responsibility for investigating the safety aspects of this issue, leading to a comprehensive research program entitled "Ride Quality of Commercial Motor Vehicles and the Impact on Truck Driver Performance," being established in 1977.

In the first few years, funding was obtained for the program to proceed into its initial phases. In the budget decision process for Fiscal 1981, Congress saw fit to question the need for the program and allocated funds for an assessment of that need. As stated in the 1981 Appropriations Bill for the House of Representatives

> ".....the bill includes the budget request of $100,000 to study truck ride quality. The Committee, however, expects that these funds will conclude this research effort and that an appropriate report will be provided delineating any truck ride quality safety problems as well as the actions required to correct any such problems."

1.2 Problem Statement

The design of trucks and tractor-trailers for efficiency in cargo transport involves compromises in "packaging" the driver. As a consequence, the driver's environment in a heavy-duty commercial vehicle characteristically involves higher vibration levels than that experienced in other transport vehicles, namely, passenger cars and buses. It has been argued that the vibration exposure of commercial truck drivers could have long-term effects on driver health, or short-term effects on the driver's ability to control the vehicle safely. If these hypothesized health and safety effects are real, certain agencies within the federal government have authority and responsibility under public law to take action which will ameliorate these effects. Further, irrespective of the significance these issues may have today, it can be anticipated that they could become more serious in the future, as a result of a continuing deterioration of the national highway system.

Ultimately, the rationale for expending federal funds on this issue depends on its seriousness in comparison to other social problems. In the ideal case, the technical community will support the legislative decision makers by providing quantitative measures of the seriousness of a problem, which can be weighed against that of other problems in society competing for federal resources. Unfortunately, the published knowledge about the effects of truck vibration on driver health and highway safety is insufficient to provide those measures.

Therefore, the objectives of this project were twofold:

1) To demonstrate experimentally the direct dependence of truck driver vibration levels on the roughness of the highway surface in order to validate the predictions that the seriousness of the issue will grow with continuing deterioration of the national highway network.

2) To assess the collective knowledge on the potential impact of truck driver vibration on highway safety in an effort to estimate the significance of the problem.

1.3 Approach

The methodology for addressing the first objective in the project is well within current technology and was approached in a straightforward manner. A tractor-trailer was acquired as a test vehicle and instrumented in accordance with the most commonly used practices to measure the ride vibrations in the cab and on the driver's seat. The vehicle was driven over a selection of road surfaces known to be representative of the general spectrum of roughness conditions. The surface roughness was measured by means of the wheel track profiles obtained by a GMR-type inertial profilometer. The truck vibration measurements were analyzed to determine spectral characteristics and other statistical measures, as commonly used to describe the properties of vibration exposure. Similarly, the road profiles were processed to obtain spectral characteristics and the summary roughness numeric commonly used by the highway community to characterize road roughness. The relationships between the road roughness and various measures of truck vibration were then examined. A detailed discussion of this portion of the study is provided in Appendix B of the report. The findings most relevant to the vibration/safety issue are presented, where appropriate, within the main body of the report.

The second objective of the project, dealing with the assessment of knowledge and estimating the significance of the vibration/safety connection, presents a more difficult problem. The approach suggested by the sponsor and agreed upon by the research staff was to convene a conference of experts for the purpose of (a) establishing a consensus on the state of knowledge, (b) obtaining their collective judgments on the importance of the issue, and (c) defining the courses of action that should be taken.

The initial steps in this phase of the project focused on the identification of a selection of experts, and design of a conference bringing the appropriate methodology to bear on the group, so as to extract the desired products. (In this latter step, consultation was obtained from experts experienced in the design of such conferences.)

A key feature of the approach involved the preparation of a state of knowledge document addressing the relationship of truck ride vibration to highway safety. The document, which attempted to provide a basic structure to the links between vibration and safety, was sent to each conferee prior to the conference in order to provoke thought and discussion.

1.4 Report Organization

This report has been arranged to present the reader with a systematic development of the knowledge surrounding the truck vibration/safety issue.

The next section (Section 2.0) reviews the state of knowledge on the various aspects of the issue as reflected in the published literature, with some of the emphasis reflecting the advice of the experts in attendance at the conference. The section encompasses (a) a characterization of the truck ride vibration environment, (b) an assessment of the potential effects of those vibrations on the driver as they might influence his performance as a vehicle controller, (c) a postulation of ways in which the accident record might be affected by vibration-related changes in driver performance, and (d) an examination of the accident record for evidence of a relationship.

Section 3.0 summarizes the findings of the conference subsequent to outlining its objectives and design. Details related to the conduct of the conference, such as the list of attendees, agenda, etc., are provided in Appendix A.

In the last section (Section 4.0), the research staff attempts to interpret and summarize the findings of the knowledge review, the ride measurements, and the conference as they apply to the issue being addressed in this project.

A detailed description of the experimental measurements of truck ride vibrations is provided in Appendix B.

2.0 STATE-OF-THE-KNOWLEDGE REVIEW: RELATIONSHIP OF TRUCK RIDE VIBRATION TO HIGHWAY SAFETY

2.1 Introduction

The ride vibrations experienced by commercial trucks and tractor-trailers are known to be more severe than those occurring in passenger cars and buses. Consequently, the highway construction and maintenance community has been sensitive to the possibility that road-induced vibrations often impact on driving comfort, highway safety, and the operating costs experienced by the road user (Brickman, 1972). Given a prognosis for a steady deterioration in the surface condition of the national highway network (Clary, 1975), the question can logically be raised as to whether the vibrations exhibited by commercial vehicles are currently impacting on motor carrier safety or, whether the current state of affairs will become a more serious problem in the future.

The question of interest has often been posed and debated in the form "Is there a relationship between truck ride quality and highway safety?" The term "ride quality" is broad based in its meaning and frequently is defined to include the vibration levels to which cab occupants are subjected and other factors such as cab noise, seating comfort, ease of operating controls, etc. (Miller, 1979). In this document, however, only the vibration component of "ride quality" is being addressed. It is also necessary to note that "highway safety" is most appropriately defined as the number and severity of highway accidents leading to personal injuries, loss of life, and property damage. On the other hand, driver health, as influenced by a long-term exposure to a vibratory environment, is frequently raised as an issue in the discussion of whether an exposure to vibration leads to degraded safety levels. In this event, it is probably advisable to employ the term "operational safety" to encompass both the risks of loss (or injury) to driver health due to long-term exposure to vibration, as well as the risks of loss (or injury) due to on- and off-highway accidents. In order to limit the scope of this state-of-knowledge review, emphasis is given to issues related to highway safety. In that context, driver health is of interest primarily as it influences the ability of truck drivers to perform their driving function or task.

When the key question is reformulated in the form, "Is there a relationship between truck vibration and highway safety?" and interpreted literally, one is forced to conclude that the answer is yes. At one extreme, it is clear that vibration constitutes a primary constituent of what is known as "road feel," a quality on which truck drivers place a great premium for safe operation. At the other extreme, one can identify incidents in which truck accidents have occurred with severe vibration identified as a major causative or contributory factor. It follows that the vibration environment in trucks does impact on highway safety, with no, or little, vibration being likely to degrade safety, and with too much being likely to cause the same result. Thus, the appropriate questions needing answers can best be stated as:

1. "What is the significance of truck vibration to the highway safety process today?
2. "Are there forces at work in the highway and trucking communities that may elevate the significance in the future?"

Clearcut answers of these questions cannot be provided by the scientific community. On the one hand, there is general recognition that the overall condition of highway pavements is degrading, and that the situation will become more critical with the pressure for increasing truck sizes and weights as a means to improve energy efficiency, and the increase in truck miles as a percentage of total vehicle miles. On the other hand, it does not appear that any definitive research findings have recently surfaced to quantify the significance of the relationship between vibration and safety as a means to gauge its importance in relation to other matters of public concern.

To facilitate a presentation of what is known regarding the negative or positive contribution of vibration to the accident record of the heavy-duty truck or truck combination, it is helpful to visualize the elements of the system as shown in Figure 1. Beginning at the left of the figure, truck ride excitation, which is dependent on many

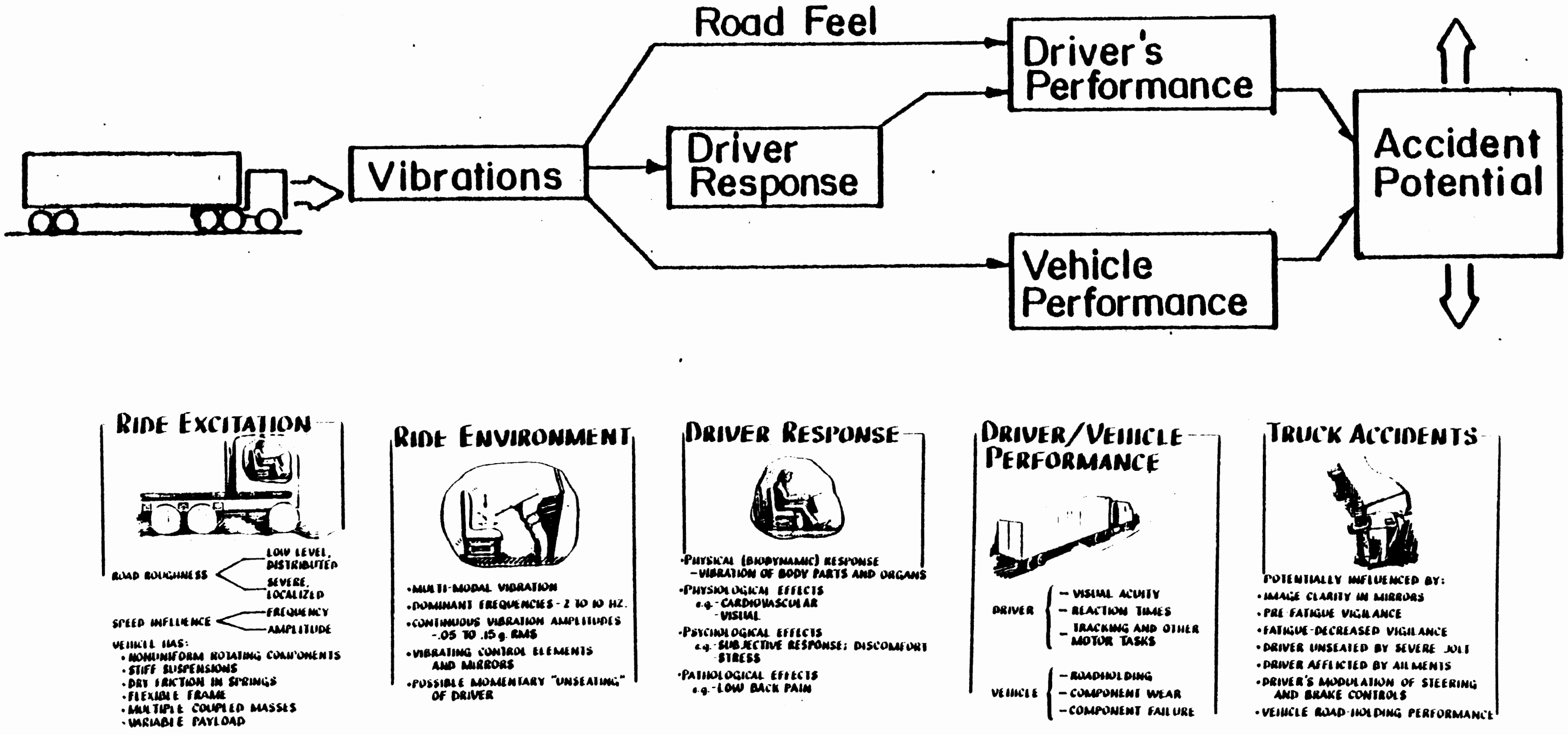


Figure 1. Pictoral representation of the primary elements in the link between truck ride vibration and safety.

factors, results in the driver being exposed to a ride vibration environment. Some aspects of that vibration contribute to the "road feel" of the vehicle having a direct, positive influence on accident potential. Of more interest here, however, is the connection whereby vibration causes direct responses in the driver's body with the potential for altering his performance as a vehicle controller, thereby affecting accident potential. Finally, it must be recognized that vehicle vibration induced by road roughness can, under some circumstances, alter the performance of the vehicle in ways that could influence accident potential.

Inasmuch as the connection through the driver is the main interest here, the elements of that connection are discussed in the three sections that follow. The vibration environment which exists in a truck cab is addressed first, both from the point of view of what prevails in a "typical" truck traversing a "typical" road surface and what can exist in an atypical truck traversing a range of road roughness conditions. Second, the effects of vibration exposure on man are addressed with regard to its potential influence on the driver as a decision maker and/or as a manual controller. We attempt to summarize what is known regarding the influence of exposure to vibration on the physiological and mental state of people, in general, and truck drivers, in particular; and we consider what is known regarding the extent to which these physiological responses to vibration interfere with the driver's ability to perform a driving task. Lastly, the review concludes with statements or hypotheses which identify the potential for vibration-induced phenomena to contribute to accident frequency and thereby influence the accident record. These statements form the basis for an examination of the accident record to see whether any of these hypotheses can be supported. Overall, the objective is to summarize the facts, including the gaps in our knowledge, in such manner as to enable reasoned and sound conclusions to be drawn regarding the answers (or the lack thereof) to the two questions posed at the beginning of this section.

2.2 The Truck Ride Vibration Environment

Since the infancy of the automotive industry, the evolutionary development of the commercial truck has been driven by its own set of unique properties. Whereas passenger cars and buses have evolved into refined machines capable of transporting passengers at a high level of personal comfort, the truck has evolved to become a highly efficient, durable machine for the transport of goods. Although driver comfort and convenience are taken into consideration, the shape of trucks today derives largely from constraints imposed by road-use laws, functional requirements, and the need to optimize its commercial efficiency.

As a result, the vibration environment to which a truck driver is exposed differs markedly from that of drivers of other motor vehicles—most notably in its severity. The characteristic differences derive from:

1) driver location—namely, the driver is usually located at the extremities of the vehicle, rather than near its center of gravity (c.g.)
2) trucks being dynamically more active at low frequencies of excitation, as caused by the use of articulation for maneuverability and frame flexibility for durability
3) truck suspension systems possessing substantial amounts of dry friction, thereby transmitting more road input to the vehicle.

The term "truck" as used here refers to two generic types of vehicles—the straight truck and the truck-tractor. A straight truck is a single-unit vehicle, in which the vocational body used to carry the load is affixed directly to the power unit. A truck-tractor is the power unit used to haul a semitrailer. Though multiple-trailer combinations ("doubles" and "triples") are in common use, their presence behind a semitrailer has no direct effect on the ride vibrations experienced by the tractor and hence these combinations need not be distinguished from the tractor-semitrailer combination.

The following discussion attempts to summarize what is known regarding the vibration environment to which truck drivers are exposed. The objective is to identify:

1) the parameters determining that environment, and
2) the knowledge gaps that must be filled to quantify this vibration environment in a thorough manner.

2.2.1 The Truck Ride Process. The vibration produced in a truck is the result of its dynamic response to various excitation sources. The resultant vibration therefore derives from the combination of vehicle response characteristics and excitation magnitudes and phasing. The excitation derives from two major sources—road roughness and on-board excitation sources.

Road Roughness has been defined (by the American Society for Testing and Materials) as "The deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic pavement loads, and pavement drainage, e.g., profile, transverse profile, cross slope, rutting." The deviations along the wheel tracks essentially excite vertical and pitch motion responses, while the differences in elevation between the wheel tracks are the major excitation of roll and other lateral motions. Road roughness derives, in part, from the random deviations which reflect the practical limits of precision to which a road surface can be constructed and maintained, and, in part, due to localized pavement dislocations and failures. The random qualities fit the general category of "broad-band random signals" and hence may be described by well-established statistical functions such as the mean-square, or power spectral density (PSD). The non-random components include periodic waves due to pavement construction or settling, and discrete dislocations. The pavement dislocations and failures may be potholes, pavement settlements in a bridge approach area, or other singular features that are not characteristic of the surrounding roadway. Road roughness is commonly quantified in terms of summary statistics (Gillespie, 1980) which do not distinguish between these two limits. For example, the PSD (measured with road profilometers), "slope variance" (measured with CHLOE instruments), or "inches/mile" statistic (derived from the suspension motions of a passenger car) do not distinguish whether the roughness measure derives from roughness uniformly distributed along the length of a road, or from one or two singular features in an otherwise smooth road. Therefore, the understanding of roads as an excitation source is limited if one only has data which determine the stationary random response of a vehicle. To identify the severe motion responses, which may occur as the result of pavement settlement at a bridge approach, the common statistical descriptors of pavement roughness are not adequate.

The random profile of a road may be characterized by elevation content, as shown in Figure 2. Though each road section is unique in its spectral density, all spectra show a characteristic diminishing magnitude with increasing wave number (i.e., spatial frequency) (Gillespie 1980). Rough roads differ from smooth roads by approximately an order of magnitude in their PSDs, and individual roads may differ from the average trend (as depicted) by an order of magnitude, or more, at specific points in the spectrum. These elevation properties become an acceleration input to the wheels of a moving vehicle, where the acceleration input has an amplitude which increases with frequency. Figure 3 shows the transformation from an elevation PSD to an acceleration PSD using an assumed speed of 50 mph. Clearly, the amplitude of the acceleration input to a vehicle on a given road is dependent on its speed. More specifically, the acceleration input magnitude caused by a given road bump increases with the square of the speed of travel (Gillespie, 1981). Therefore, speed has a first-order influence on the manner in which road roughness excites a motor vehicle.

The road presents no lateral acceleration input to a vehicle directly, but rather, the elevation differences between the wheel tracks constitute a roll input that may be perceived as lateral acceleration by the driver. The roll excitation is quantified most understandably by comparison against the corresponding vertical input on a given road. Figure 4 shows the ratio of spectral densities for the roll and bounce inputs on a typical road. As seen in the figure, the roll input tends to be only a fraction of the vertical bounce magnitude in the low wave number band corresponding to low frequency excitation of a vehicle traveling at normal speeds. In most cases, roll input only becomes comparable

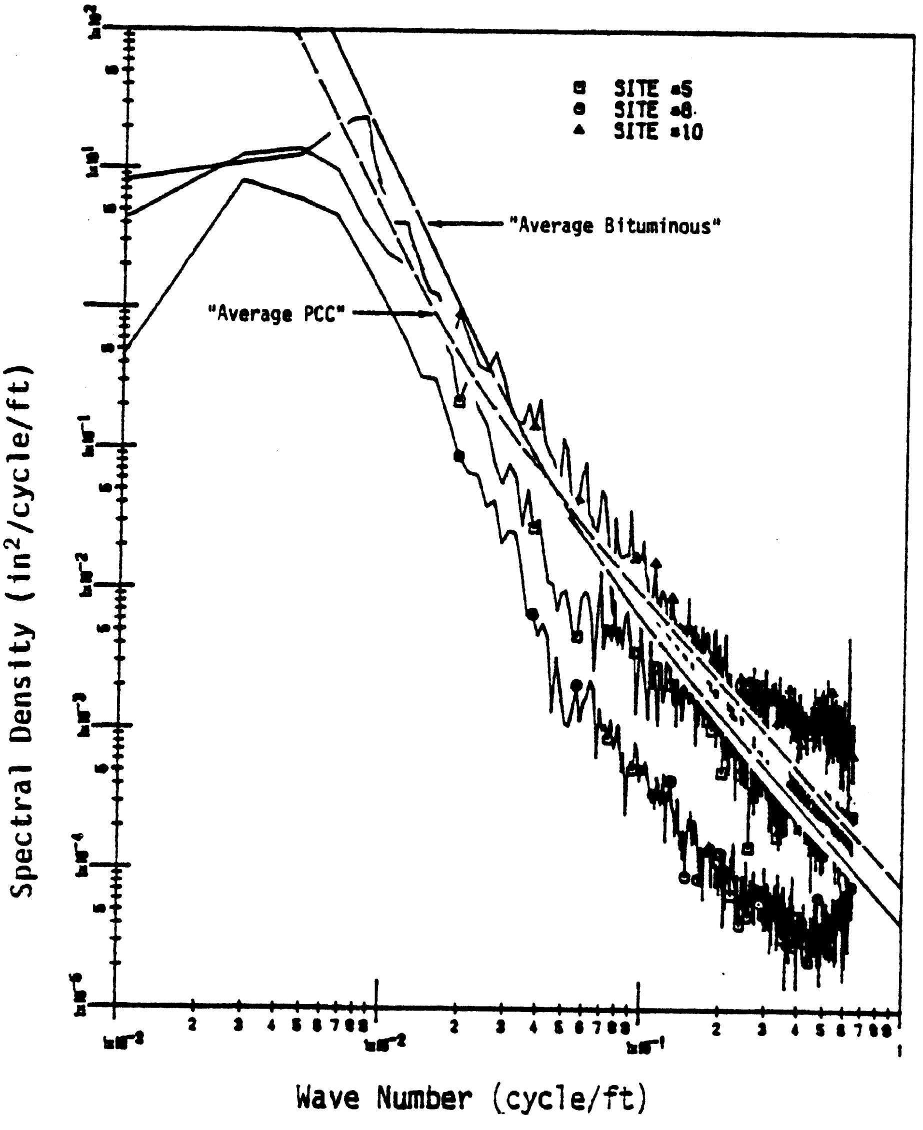


Figure 2. Typical spectral densities of pavement elevation (average of two tracks).

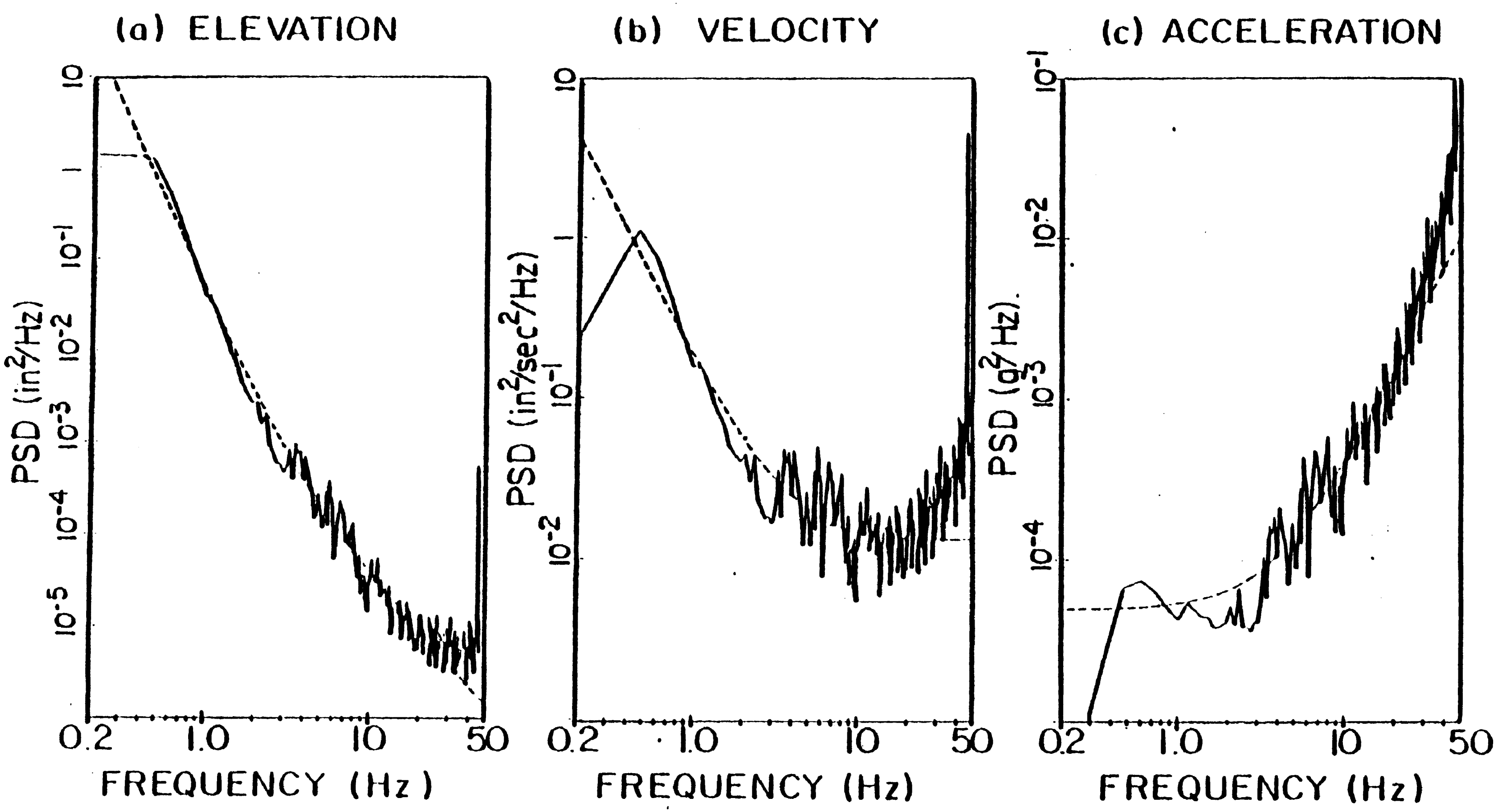


Figure 3. Elevation, velocity, and acceleration PSD's of the road roughness input to a vehicle traveling at 50 mph on the real and model roads from Figure 3.

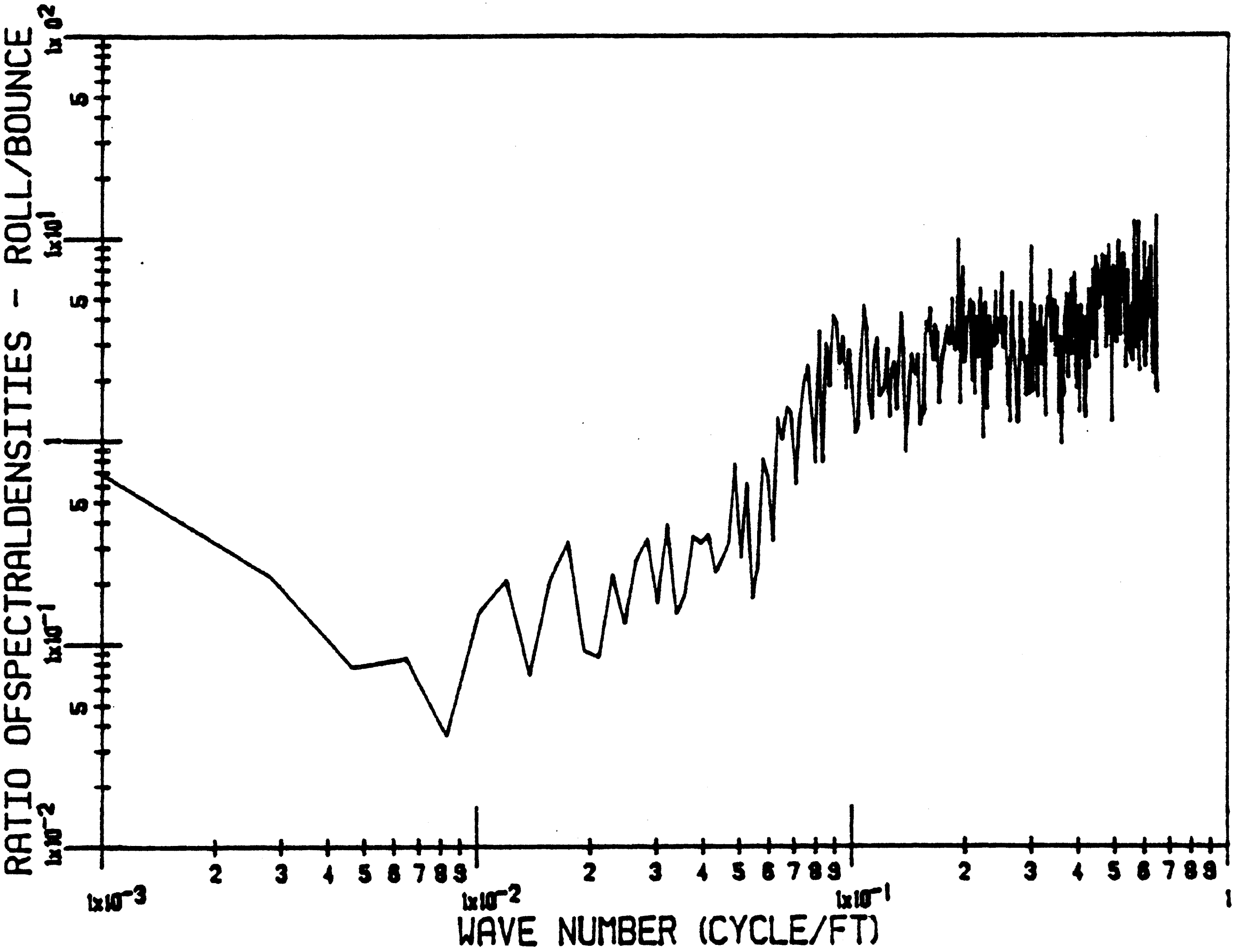


Figure 4. Ratio of roll to bounce spectral densities for a typical road.

to the vertical input at higher wave numbers. Because of the low resonant frequencies of vehicles in roll, the roll excitation at normal highway speeds (which arises from the lower band of wave numbers) is generally less significant than the vertical excitation.

On-Board excitation sources are the rotating components of the vehicle including engine, drivetrain, and wheels. The engine and drivetrain frequencies are always higher than wheel frequencies by virtue of the gear ratios by which their angular speeds are related. An exception to this rule is the case in which the engine/transmission may serve as a resonant mass on the vehicle (Stimeling, 1965). By and large, nonuniform wheels and tires constitute the major on-board vibration source, primarily during operation on smooth roads (Gillespie, 1979). A nonuniform, rotating tire and wheel results in excitation at the rotational frequencies and each harmonic thereof. Should any of the spatial harmonics at the wheel (e.g., whole ratios or fractions of the circumference) be the same as a roadway spatial wavelength, strongly resonant conditions could develop (Jex and Zettner, 1981). The multiple wheels on the vehicle may also vary in their phase relationships, working together at various times to create bounce, pitch and roll excitation. Although tires and wheels serve as vibration excitation mechanisms at all times on all vehicles, their influence on the vibration spectrum is most apparent on smooth roads (Ervin, 1979), as illustrated in Figure 5. On a rougher road, the same wheel excitation causes a smaller influence, as shown in Figure 6, due to the greater damping that results with the larger deflections of the leaf spring suspensions which prevail on rough roads (Sayers, 1981). Thus, as a general rule, truck ride vibrations tend to exhibit more periodicity on smooth roads than on rough roads due to lower effective suspension damping, and due to the prominence of wheel excitation compared to roadway excitation at the first and higher order harmonics of wheel rotation. In general, wheel-excited vibration is a common cause of customer dissatisfaction, motivating vehicle manufacturers to give considerable attention to this problem in manufacturing control. However, the phenomenon is difficult to control in the field, in that it can be a strong vibration source with poor wheel maintenance or when tires have been "flat spotted" from a braking skid.

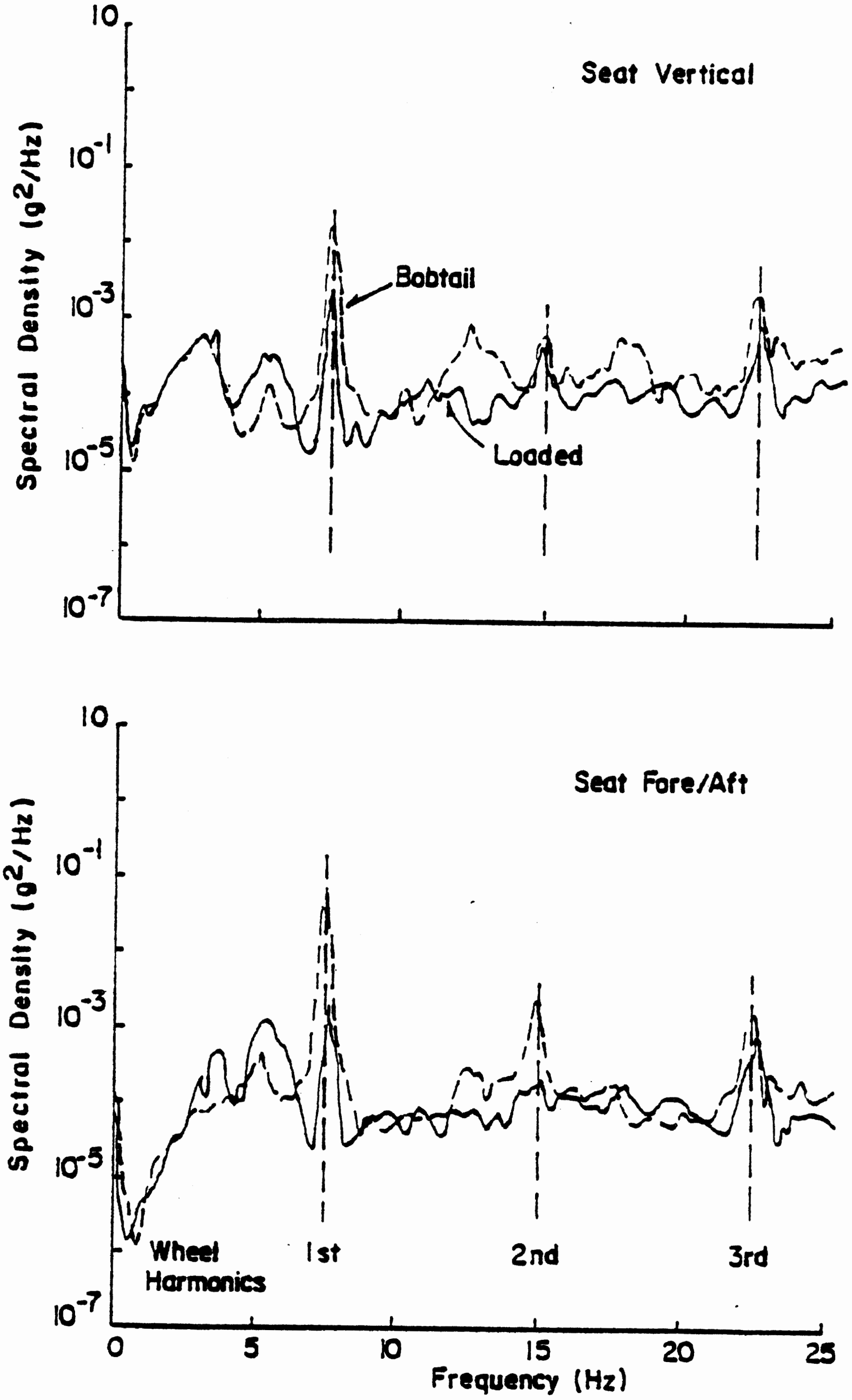


Figure 5. PSD's of bobtail versus loaded combination - COE tractor, 55 mph, on a smooth road.

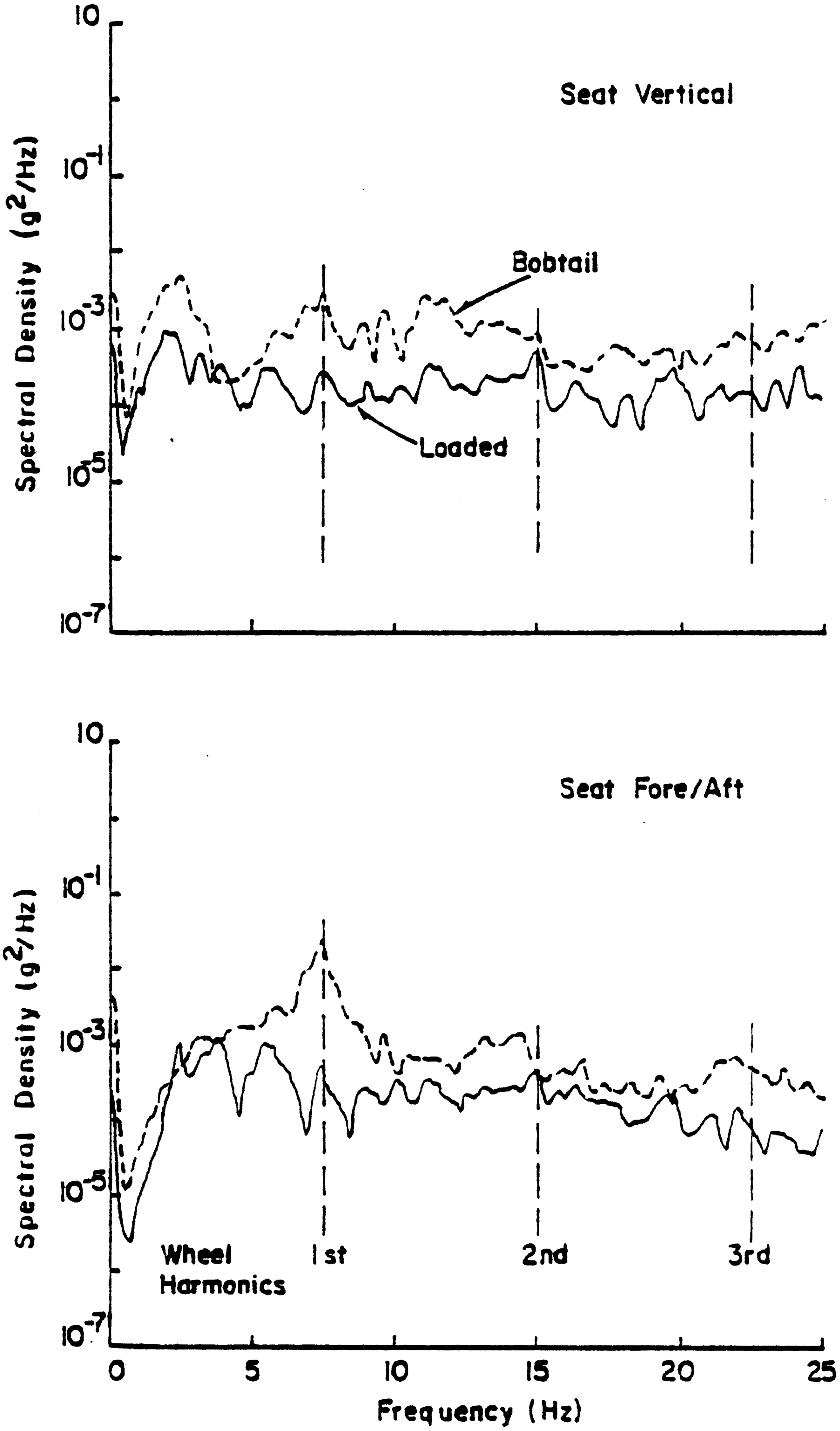


Figure 6. PSD's of bobtail versus loaded combination - COE tractor, 55 mph, on a rough road.

Truck Vibration Response. The motor truck is a complex dynamic system responding to excitation inputs from the roadway and wheels. Because a full discussion of the state of knowledge would be quite lengthy, only a few key elements are discussed here.

The vibration environment on a truck derives, in part, as a consequence of the dynamic response inherent to that configuration of a vehicular system and, in part, as a consequence of the specific design or operating conditions of the vehicle. In the low-frequency regime, the vehicle system acts as a "rigid" body separated from the road by its running gear and its suspension systems. On viewing the motor vehicle as a simple two-mass system, the manner in which the suspension acts to attenuate road inputs becomes clear, as illustrated in Figure 7. However, real vehicles making contact with the road at numerous points respond in pitch and roll as well as in bounce or heave. Further, the road input along one track of the vehicle is the same for every wheel but delayed in time, according to the speed of travel. If the road is assumed to possess a cylindrical profile such that right and left wheels see the same profile, a random road input will elicit the vibration response shown in Figure 8, as calculated for a tractor-semitrailer (Dokainish, 1980).

An examination of Figure 8 shows that vertical vibration is dominated by a peak associated with the sprung-mass resonance. This peak is always present and well defined in trucks and tractors, although the exact frequency may vary over the range of 1-4 Hz, depending on the suspension system and the operating conditions. On the other hand, the fore/aft acceleration response derives primarily from the pitching motions of the vehicle. This latter response tends to be rather sensitive to "tuning" between the vehicle and road. Specifically, pitch excitation caused by road bumps passing first under the front and then the rear wheels occurs only at certain frequencies which depend upon the ratio of speed to wheelbase, as shown in Figure 9. At normal highway speeds, pitch excitation is maximum in the range of 3-5 Hz. As a result of their design, many of the shorter wheelbase cab-over-engine tractors have pitch resonances in this range. (In general, the longer tractor and the straight truck are less tuned to this mode.)

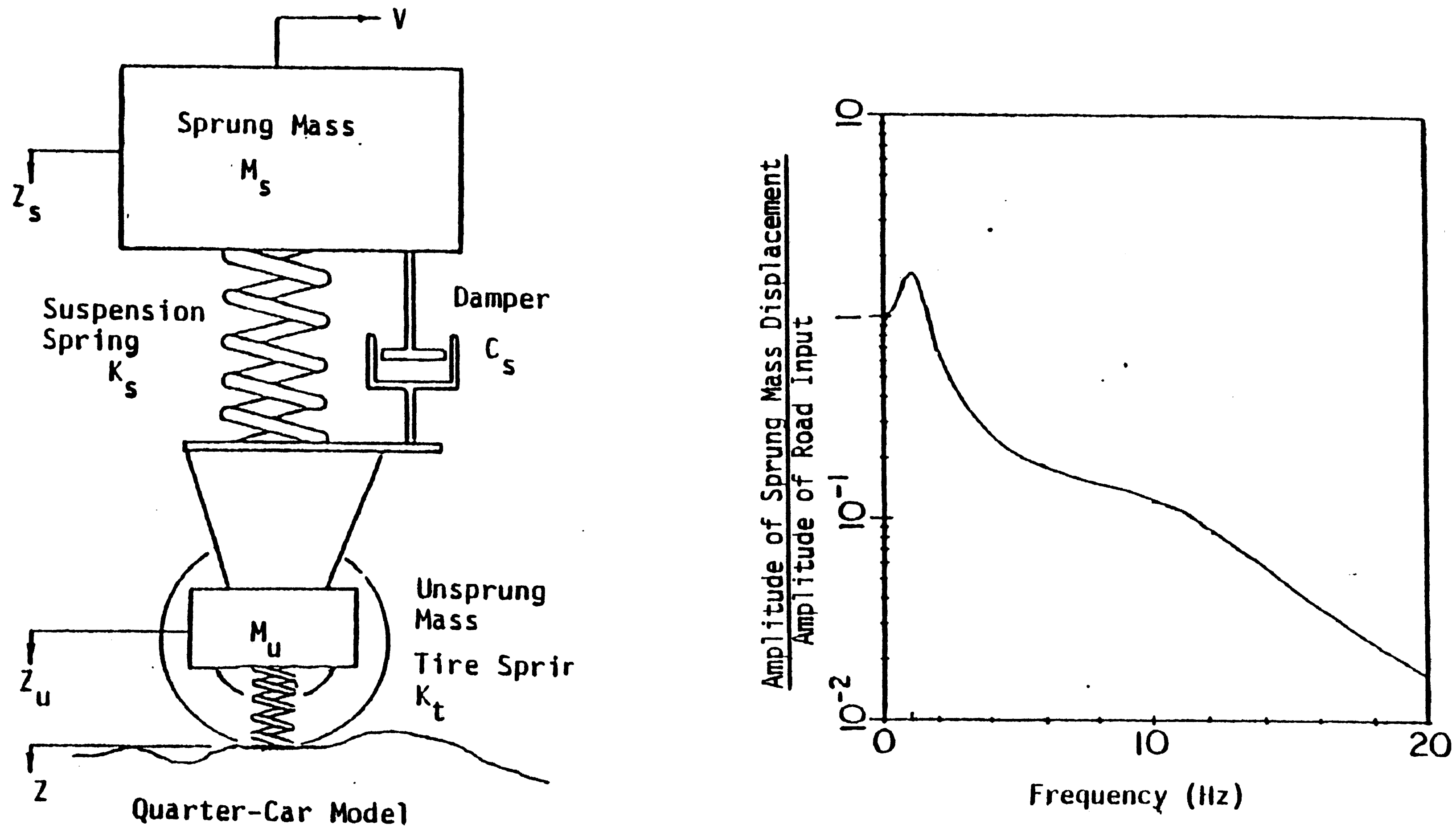
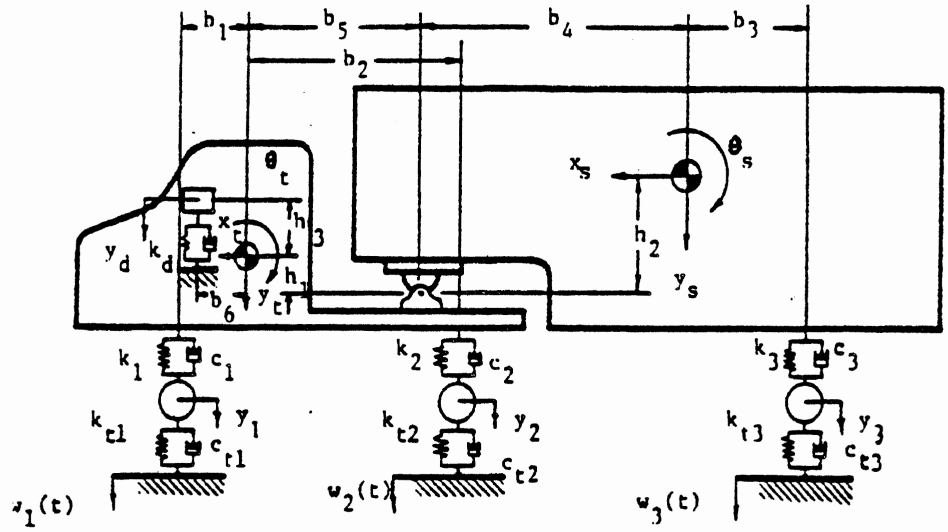
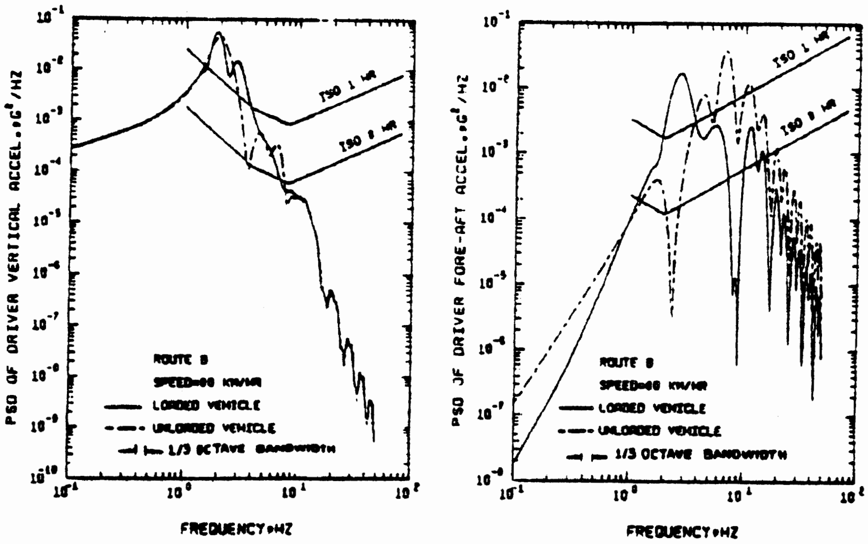


Figure 7. Isolation of a vehicle body from road input deriving from a quarter-car model.



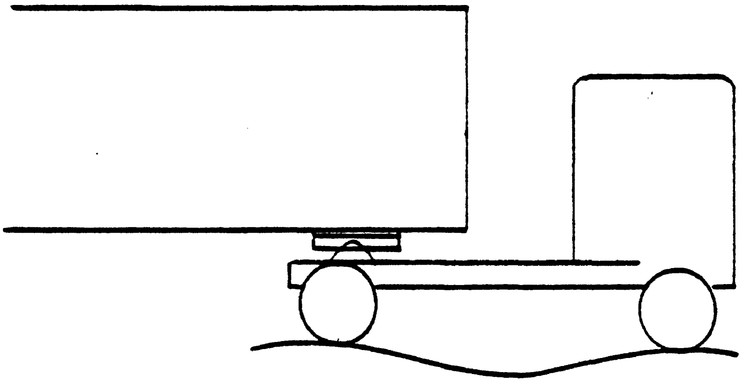
Tractor-semitrailer model.



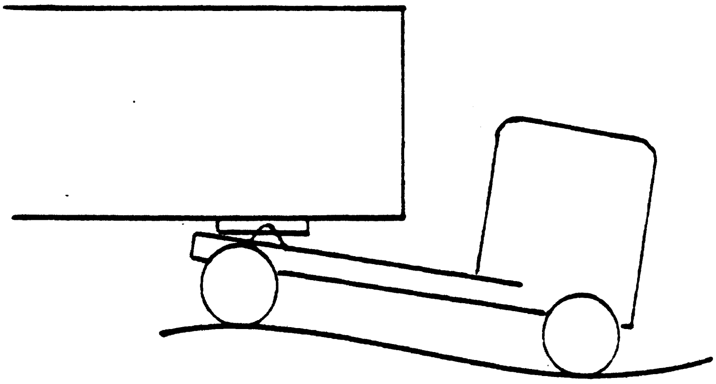
Vertical and fore and aft acceleration spectra – rough road.

Figure 8. Calculated acceleration response of a multi-degrees-of-freedom tractor-semitrailer model to random road input.

Note: The ISO curves shown in the bottom figures are for the "reduced comfort" boundary.



FULL BOUNCE EXCITATION, NO PITCH



FULL PITCH EXCITATION, NO BOUNCE

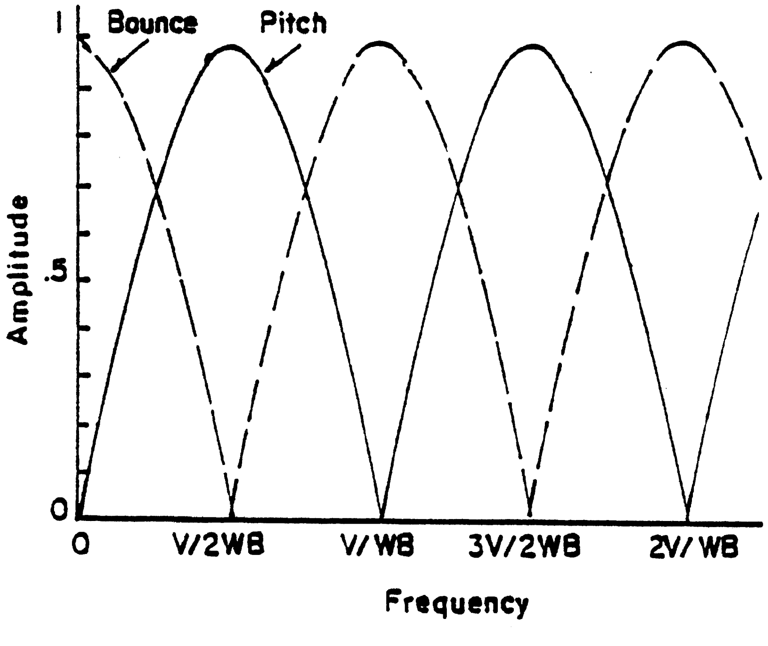
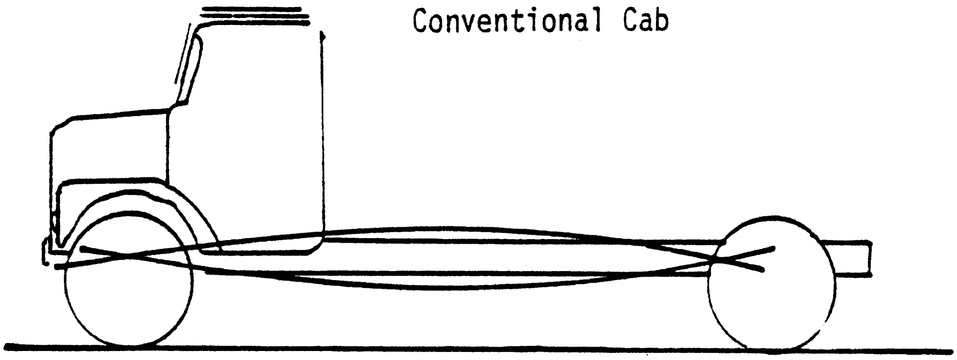


Figure 9. "Wheelbase filtering" causes a vehicle to not respond to certain road frequency inputs.

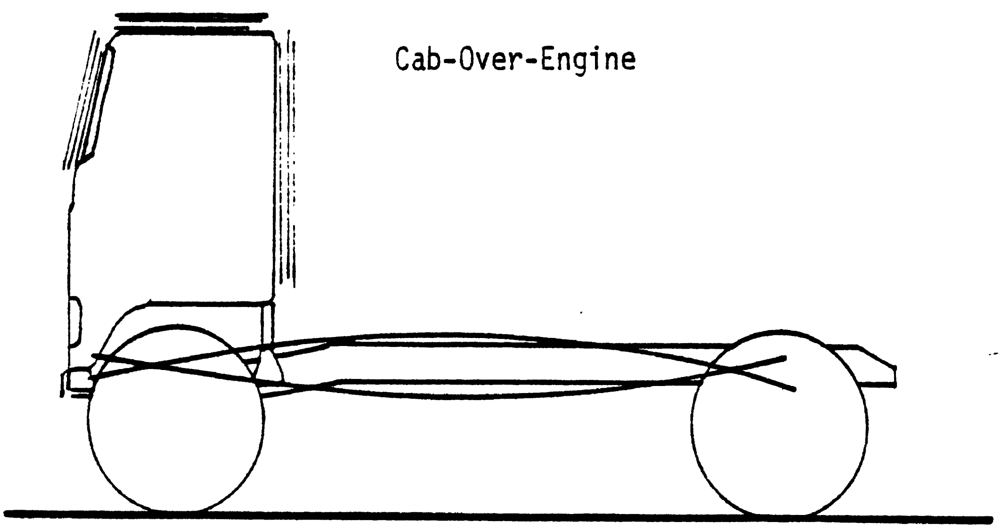
The above-described effects explain the dominant low-frequency vibrations present on a truck or tractor, but are by no means the complete picture. Vibration measurements on trucks have shown many other possible modes of vibration beyond those exhibited by the "rigid" body. Typically, the vertical bending mode of the frame, as illustrated in Figure 10, is quite important and may occur in the range of 6-9 Hz. In addition, other resonant modes will be present, as shown in Figure 11.

The exact behavior of the vehicle and the degree to which these various vibration modes influence the vibration environment within the vehicle cab are dependent on the specific design of the vehicle frame, the cab mounting system, and the location of the fifth wheel which joins the trailer to the tractor. In general, one finds that as many as several dozen vibration modes, with frequencies ranging up to 20 Hz, contribute to the total ride response of the vehicle. The degree to which these numerous modes are present and are significant determinants of the overall vibration spectrum depend upon the specific design actions adopted by the vehicle manufacturer in order to satisfy simultaneously the detailed specifications prepared by the purchaser and the road-use laws prevailing in the states in which the vehicle will be used. In the process of satisfying these requirements, road-use laws influence the low-frequency rigid-body response of the truck but exercise marginal influence on the high-frequency vibration behavior of trucks.

2.2.2 <u>The Truck Driver's Environment</u>. The magnitude of the vibrations present on a truck vary not only with time, but with location on the vehicle. Thus, the fact that the driver is located forward, above, or to the side of the center of gravity has some influence on his environment. The cab is normally isolated, to some extent, from the rest of the vehicle, and the driver is further isolated from the motions of the cab by a seat which contains cushioning material and frequently its own suspension system. Though the truck manufacturing industry has implemented design improvements over the years to improve the driver's environment (Hanna, 1979), it must be recognized that the ultimate goal cannot be complete isolation of the driver from vehicle vibration. Complete isolation from the vibrations which abuse, deteriorate, or even cause tires,



Conventional Cab



Cab-Over-Engine

Figure 10. Illustration of frame beaming vibration of a conventional and a cab-over-engine truck.

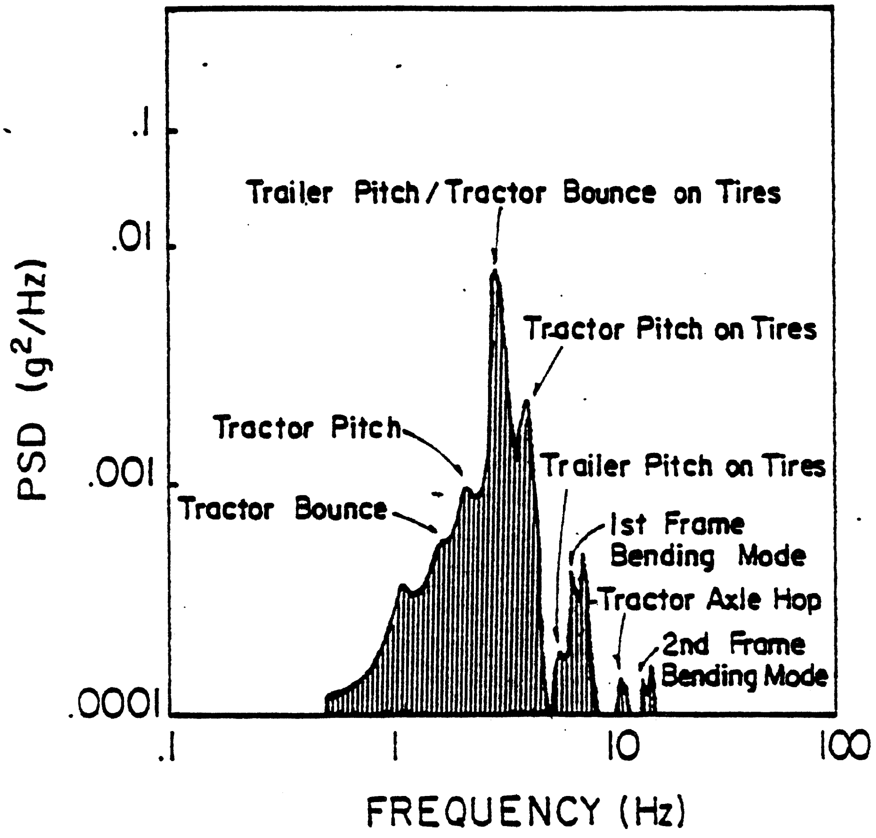


Figure 11. Typical PSD of vertical cab acceleration for a tractor-trailer (Crosby, 1974).

steering, suspensions, and other components to fail would most certainly constitute a safety hazard. In addition, it is well recognized that the "road feel" essential to safe driving, at least in part, consists of vibration feedback; although there are no quantitative guidelines to suggest how much feedback is necessary, what portions of the spectrum are most important, or how it is perceived by the driver.

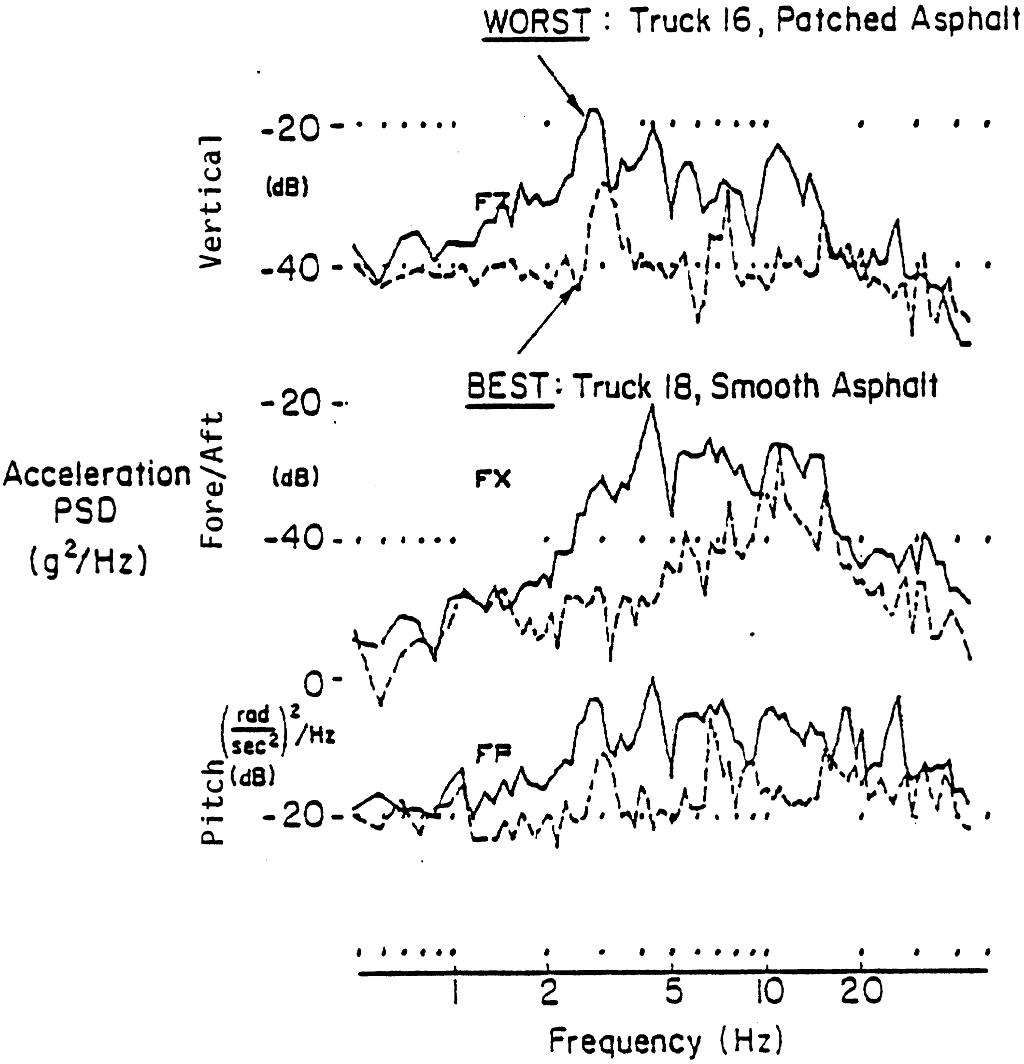
Excluding noise, the vibration perceived and felt by a truck driver can be broken down into four categories for discussion purposes, viz.:

1) vibration of mirrors and instruments
2) input through the steering wheel and controls
3) input through the floor and foot controls
4) direct (whole-body) vibration input through the seat

By and large, much of what is known about driver exposure to vibration is concentrated in measures of acceleration on the seat or at various points on the cab structure. Although the vibration of external mirrors, either as a result of aerodynamic buffeting or cab vibration, may obsure vision to the rear, little has been done to quantify the magnitude of this problem, either at the as-built stage or at the vehicle-in-use stage. It appears that most truck drivers have encountered this problem at some time or other, since nearly 50 percent of the respondees in an informal PROD survey (Wilson, 1979) indicated moderate (or greater) effects of vibration on the use of mirrors and instruments. Similarly, no data exist to quantify the vibration input to the truck driver through the steering wheel and/or other hand-operated controls. As a first estimate, one could assume that typical cab vibration levels prevail at the various hand controls. However, it should be noted that the steering wheel and transmission shift lever, with which the driver has the most extended hand contact, are both somewhat decoupled from the cab structure and are exposed to excitation sources which are largely decoupled from the cab.

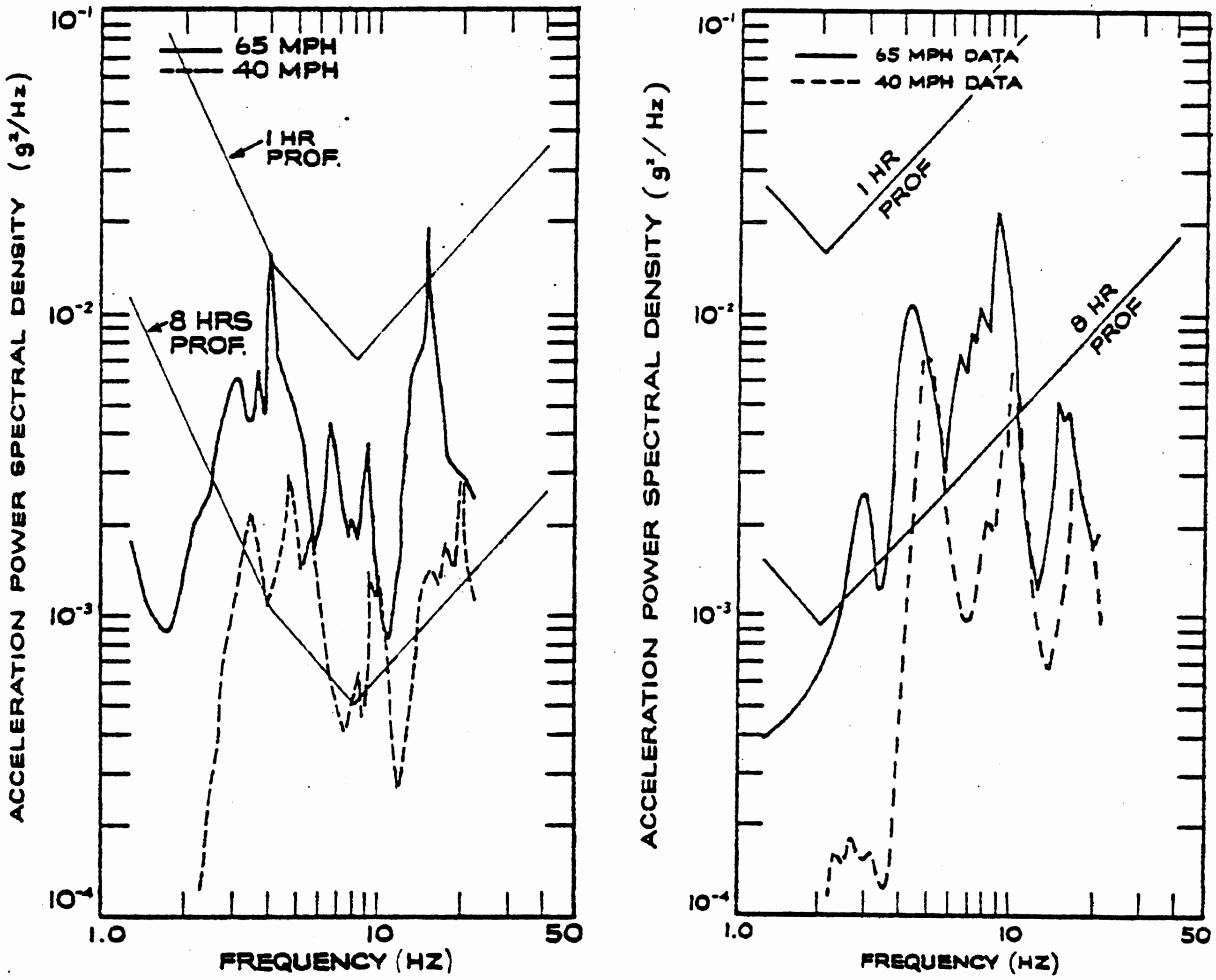
Input Through the Floor or Through Foot-Operated Controls. Truck cab vibrations have often been measured at the floor, either at the seat base or above the front- and rear-cab mounting points. In weighing such data, however, it should be recognized that the driver's feet may not be tightly coupled to the surface because they do not carry his weight and that floor mats or other cushioning materials may be present in the cab.

A FHWA-supported study (Jex, 1981) provides the most comprehensive picture of the acceleration present in commercial vehicles in the U.S. by providing a base of comparable measurements on a number of trucks under varying operating conditions. Figure 12 shows the vertical and fore/aft acceleration spectra which exist at the floor in the best and worst case trucks encountered in that study. The data have been first-order low-pass filtered at 53 and then 40 Hz in the processing so that some of the attenuation seen at higher frequencies derives from the filtering. Note that in the examples presented earlier (Figures 5 and 6), no significant attenuation of the spectrum was evident out through the upper frequency limits of 25 Hz. Thus, entirely consistent data do not exist by which to precisely define the bandwidth of the vibrations which are present at various points on trucks. Common practice, as guided by the knowledge of human tolerance to vibration, has led researchers in truck vibration to focus their interest in the frequency range extending up to about 25 Hz. In that range, most of the vibration energy tends to be observed between 2 and 20 Hz. For the worst case vehicle of Figure 12, the largest amplitudes may be recognized as being caused by (1) rigid-body motions in bounce and pitch as occur in the range of 2-5 Hz, (2) frame bending and other complex modes in the range of 5-10 Hz, and (3) unsprung-mass resonance which occurs at, or just above, 10 Hz. These patterns, spanning several orders of magnitude in amplitude, are typical and may be seen in data reported by others. Comparable to the data presented in Figures 5, 6, and 12, data obtained with another conventional tractor show the same characteristic spectra, as demonstrated in Figure 13. The lowest frequency (bounce) resonance in the vertical acceleration spectrum is evidence of the effect of speed on the amplitude of the input acceleration, whereas the reduction in the 3-Hz longitudinal resonance (rigid-body pitch mode) associated with the 40-mph case is the likely result of "detuned" pitch excitation as results from a specific combination of speed and wheelbase.



a) Cab Floor

Figure 12. Typical best and worse case cab floor acceleration spectra on a tractor-semitrailer combination (Jex, 1981).



Vertical

Longitudinal

Figure 13. Typical cab floor acceleration spectra showing effect of different operating speeds. (Crosby, 1974)

Note: The use of ISO 1- and 8-hour Fatigue-Decreased Proficiency boundaries for human tolerance to vibration are not considered meaningful as used here (Von Gierke, 1982).

The spectra alone do not provide a good quantitative measure of acceleration intensity. In the FHWA study (Jex, 1981), RMS levels of acceleration occurring at the cab floor were also determined (see Fig. 14). In general, the vertical component of acceleration tends to be greater than the fore/aft component. Both components increase with road roughness, ranging from the lowest values on smooth asphalt (SA) to highest on patched asphalt (PA). Typical values range from a minimum of 0.05 g's to a maximum of 0.20 g's. Not surprisingly, the highest magnitudes of fore/aft acceleration tend to show up on the short-wheelbase cab-over-engine vehicles.

Direct Vibration Input Through the Seat. Limited data have been published in recent years which characterize the whole-body vibration input to drivers of highway tractors, as exist at the driver/seat interface. These data are broadly characterized by the acceleration spectra shown in Figure 15. The spectra are quite similar to those measured on the vehicle floor with the exception that, at frequencies above 5 Hz, the spectra amplitude is somewhat attenuated by the seat suspension. Figure 16 shows similar measurements, as obtained at the seat of a straight truck (Mehta, 1981). Both types of vehicles exhibit characteristic resonances in the resultant spectra. The straight truck (see Fig. 16), like the long-wheelbase, conventional tractor (see Fig. 15), tends to exhibit lesser levels of fore/aft acceleration than vertical acceleration.

The acceleration spectra measured at the driver/seat interface exhibit a complex waveform whose shape is difficult to interpret on a quantitative basis. Some insight can be gained by examining the spectra on a linear-linear scale in which case the area under the curve represents the mean square value of the acceleration over the bandwidth considered. Figure 17 shows the seat acceleration spectra for the tractor tested in this project (see Appendix B) on rough and smooth roads. For the loaded tests shown, the major portion of the mean square seat acceleration in both the vertical and fore/aft directions is concentrated in the 2.5-5.0 Hz band, indicating that most of the RMS acceleration

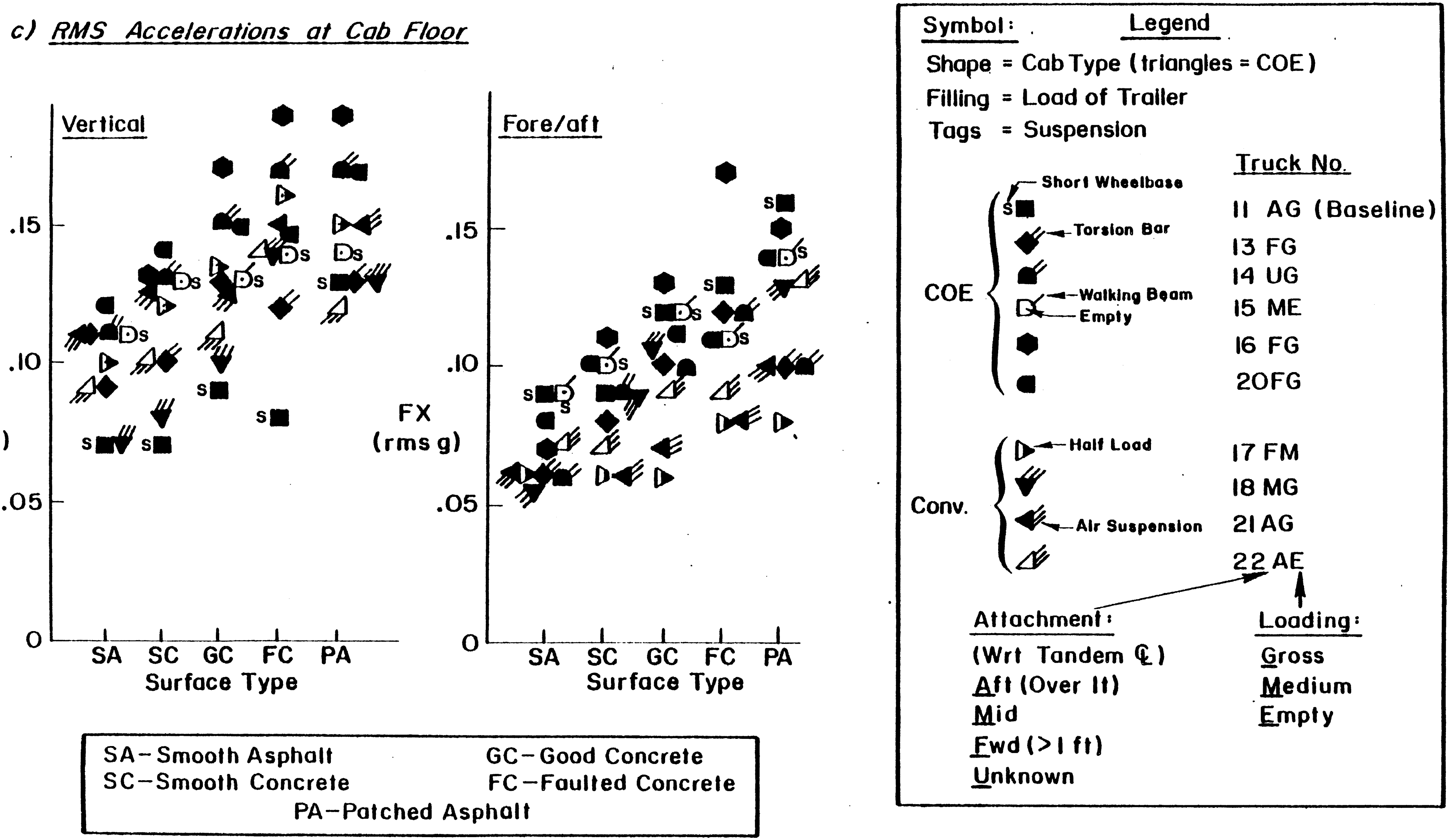


Figure 14. RMS acceleration levels measured on the tractor and cab floor of ten vehicles on five road types (Jex, 1981).

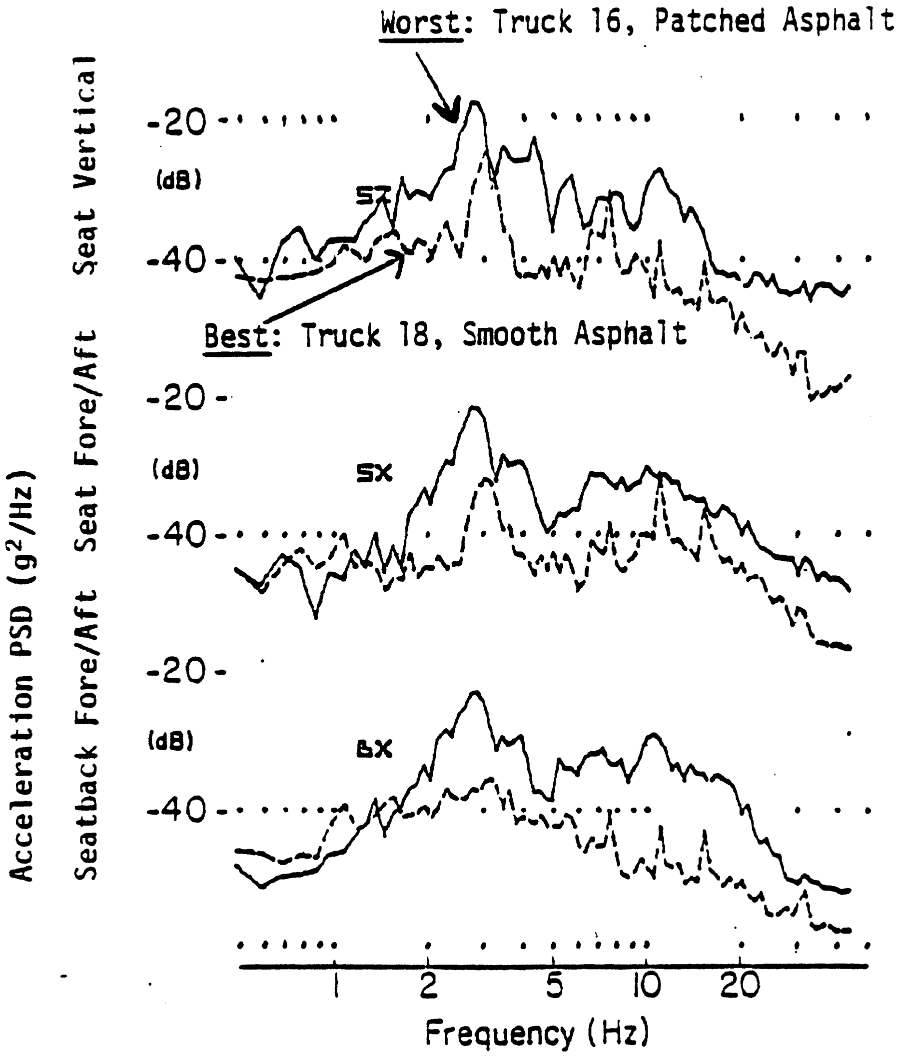
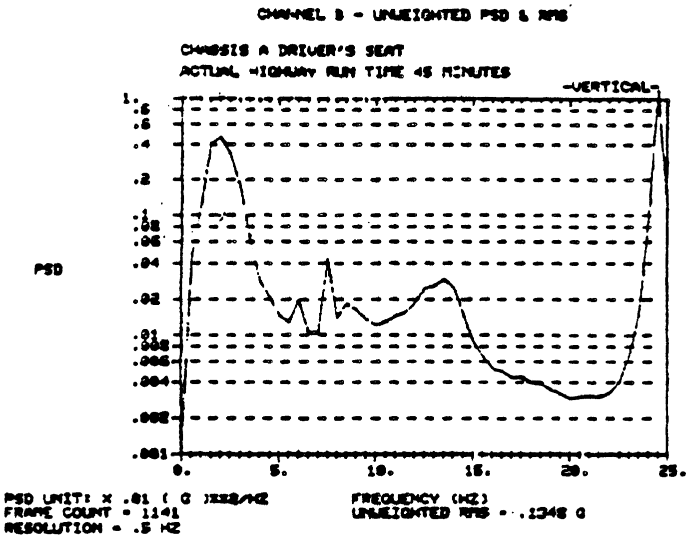
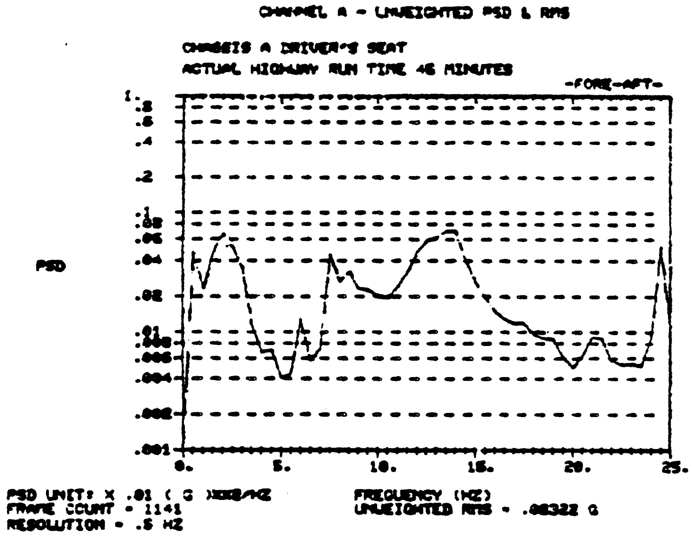


Figure 15. Typical seat acceleration spectra for best and worst case tractor-semitrailer combinations (Jex, 1981).



Unweighted root mean- square accelerations - Driver's position - Vertical direction



Unweighted root mean square accelerations - Driver's position - Fore-aft direction

Figure 16. Typical seat acceleration spectra measured on a straight truck (Mehta, 1981).

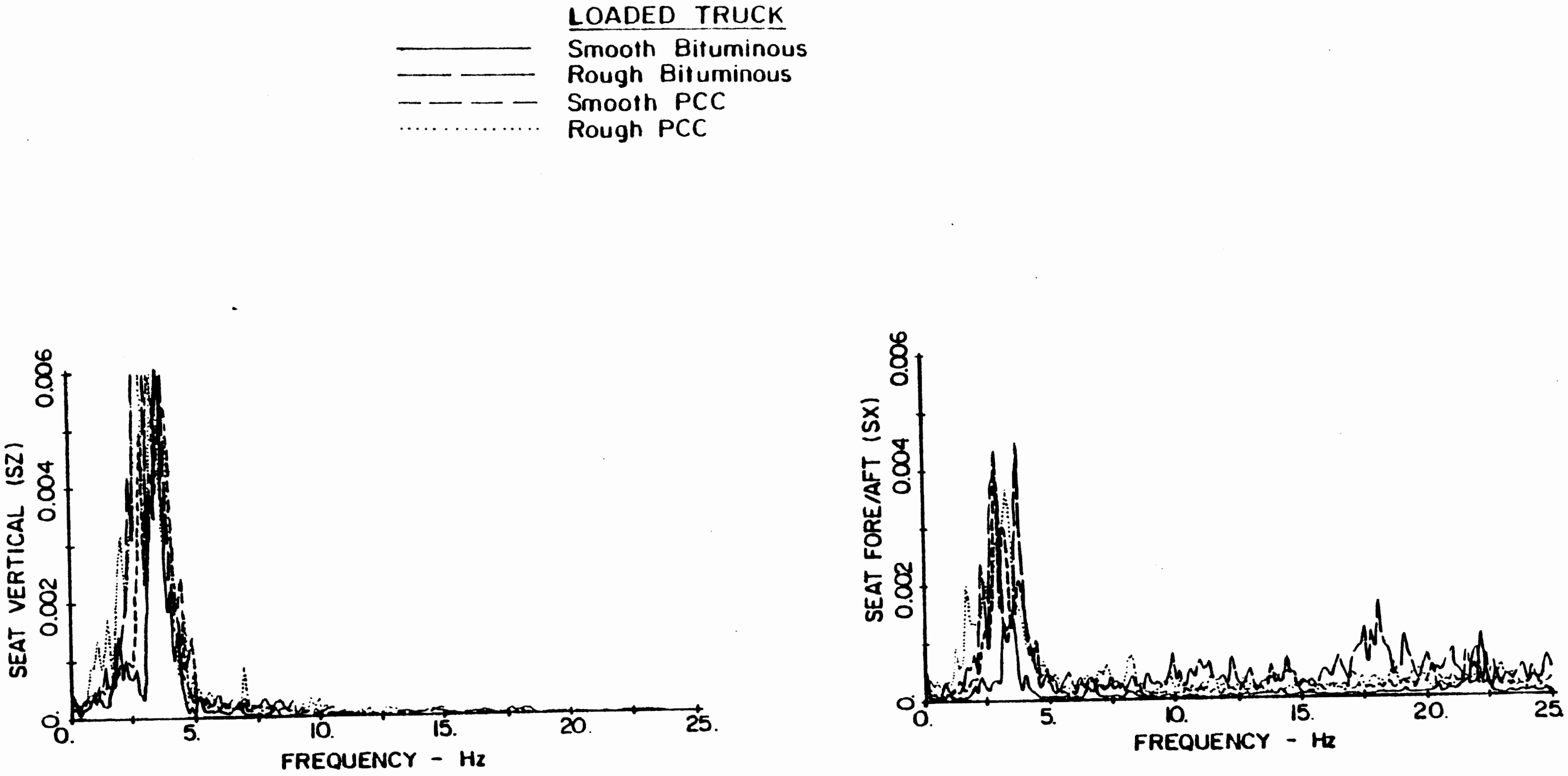


Figure 17. Seat acceleration spectra for a loaded tractor plotted on linear scale to illustrate frequency distribution of the mean square value.

getting through to the driver via the seat comes from the low-frequency, rigid-body vibration modes. (When unloaded, the vertical acceleration tends to be more distributed across the spectrum.)

The most broady accepted summary measure of whole-body vibration environment appears to be the ISO-weighted value of RMS acceleration (ISO, 1978). The ISO method, which is discussed in more detail in Section 2.3.7, weights the accelerations in accordance with the human body's tolerance to vibration, and suggests limits for exposure appropriate to preservation of health (or safety), working efficiency, and comfort. The limit for working efficiency, known as the Fatigue-Decreased Proficiency (FDP) boundary, is the most commonly used criteria for judging vibrations that may affect performance in driving a vehicle.

Figure 18a shows the ISO-weighted RMS seat acceleration levels for a number of tractors and conditions as measured by Jex (1981) in the FHWA study. As reported here, these data represent the RMS value for the overall acceleration spectrum after it is weighted in accordance with the ISO sensitivity curves (the "weighted overall acceleration method"). However, the one- and four-hour FDP boundaries shown are applicable to the RMS acceleration contained in only one third-octave band. Comparison of the RMS for the whole spectrum against the limit for only a third-octave band is permitted in the Standard as an approximation to simplify measurement and evaluation because, in most practical cases, the difference between this method and the method of choice is usually small and always conservative. Nevertheless, in cases where evaluation by the weighted overall acceleration method results in impermissible levels, the user is instructed to evaluate the limits for each third-octave band of the spectrum. Figure 18b shows data for the same vehicles evaluated by the third-octave band method. In this case, the third-octave band RMS values (reported in the appendix of the Jex (1981) report) were each adjusted in accordance with the ISO weighting factors; then the weighted RMS value for the most critical third-octave band is plotted for direct comparison against the exposure limits. On the basis of the recommended method for evaluation shown in Figure 18b, it would appear that <u>most tractors under most driving conditions would be</u>

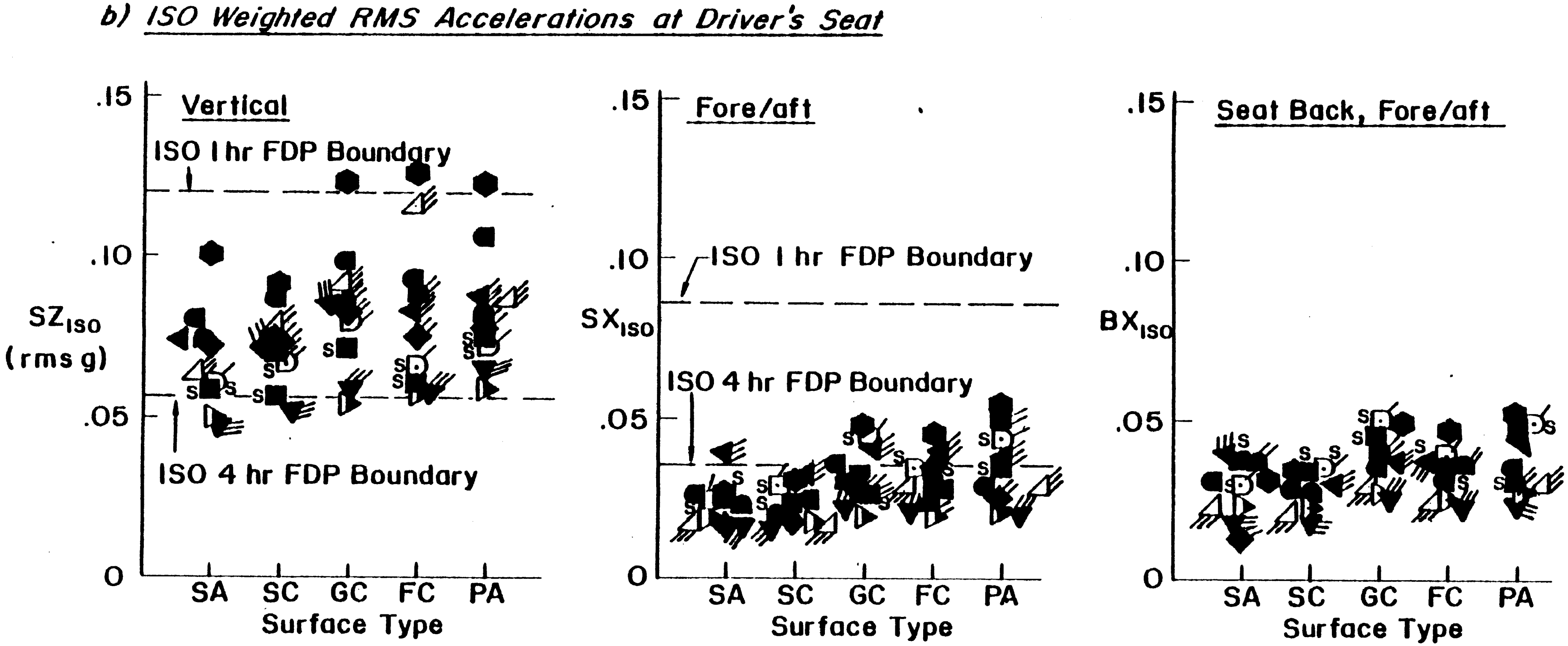


Figure 18a. Weighted overall RMS acceleration levels on the seat of tractor-semitrailer combinations on different roads (Jex, 1981).

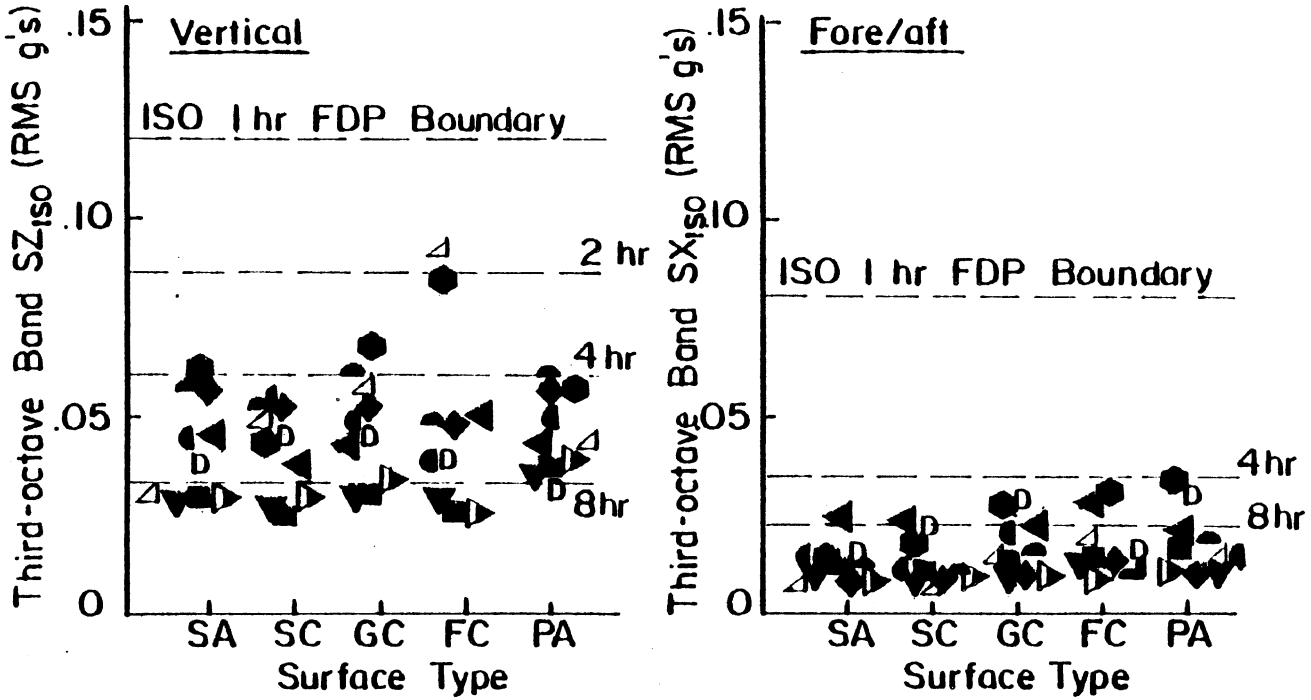


Figure 18b. Weighted one-third octave band RMS acceleration levels on the seat of tractor-semitrailer combinations on different roads (plotted from Jex, 1981).

permissible for at least three or more hours of exposure. Under worst case road conditions, the limit might drop to about two hours if that road condition existed for extended distances. Most of the vehicles and roadway conditions reflected in Figure 18 were subjectively rated by the drivers as causing "none" to "mild" discomfort. Only one vehicle falling at the high level of vertical vibration was rated as causing "strong" to "extreme" discomfort.

The small amount of data reported by Mehta (1981) in his study of straight trucks produced ISO-weighted RMS values on the particular test route used in that study which are in the mid-range of the values measured by Jex, as shown in Figure 18a. The equivalent third-octave band values for Mehta's data are not available.

A second summary measure of vibration magnitude which is used by some to scale the vibration environment experienced by humans is the absorbed-power concept developed by Pradko and Lee (1968). Using this scale, Foster (1978) reports absorbed-power levels of three watts vertical and nearly four watts longitudinal on a "typical" loaded COE tractor running on a secondary road. It is implied by Foster that much more acceptable ride is equated with one watt of absorbed power along each axis. Mehta (1981), in his study of straight trucks, measured absorbed-power levels of less than one watt for his selected test route.

2.2.3 Truck Ride Dependence on Road Roughness.

As indicated earlier, road roughness is a primary excitation source of truck ride vibrations. Road roughness is routinely measured by many state highway agencies as an indicator of pavement condition. However, the measurement methods are keyed to discerning the roughness qualities that most impact on the ride comfort obtained in passenger cars, because passenger cars represent the numerical majority of road users. It is an ongoing concern as to whether these measures of roughness adequately detect the roughness qualities in a road surface of importance to commercial vehicles, such that future efforts by the highway community to maintain minimal roughness levels within the road network will be responsive to the commercial vehicle users as well as the passenger-car-driving public.

The most popular method of measuring road roughness involves the response-type measuring system, often called a "roadmeter" (Gillespie, et al., 1980). The device consists of a host vehicle (a passenger car or two-wheel trailer with similar dynamic characteristics) in which a meter is mounted to detect the motions across the rear suspension. The suspension deflections are rectified and summed over a unit distance of travel along a road. The roughness is then quantified as an "Inches/Mile" statistic ("Inches" of suspension deflection per "Mile" of distance traveled). Such a measure is obviously sensitive to the mechanical properties of the host vehicle, the measurement speed, and many other variables. However, a standardized measure of a comparable statistic has been proposed (Gillespie, et al., 1980) and used to calibrate roadmeters from a number of states. That statistic, the "RARV" (standing for Reference vehicle Average Rectified Velocity) is a measure of the nominal suspension deflection rate in "Inches/Second" caused by road roughness. It is closely related (by amplitude and spectral content) to the body accelerations that occur on the reference vehicle and may be mentally interpreted as a surrogate measure of body acceleration response to roughness for a typical passenger car in the following discussion. The RARV measure will be used to quantify roughness level in the remainder of this discussion.

Relationship of Truck Ride to Common Highway Roughness Measures. Data to indicate how truck ride vibration levels relate to the common measures of road roughness do not exist in the literature. Therefore, a limited study was conducted within this project to obtain a preview of the relationship that exists. (Details are given in Appendix B.)

A two-axle COE tractor was run at various speeds over a number of roads having various roughness levels, while accelerations on the cab floor and seat were measured. The road sites were measured by a GMR-type profilometer from which data it was possible to determine the roughness in "Inches/Second" on the RARV scale. On this scale, the very best roads are at the nominal limit of 0.5 I/S; at 2.5 I/S, the road is considered marginal by most users; and at 3.0 I/S, the road is considered unacceptable by virtually all road users. Figure 19 shows the vertical acceleration levels measured at the driver's seat and on the cab floor as a function of road roughness level, whereas Figure 20 shows comparable results for longitudinal acceleration. It may be observed that the accelerations on the tractor floor have a first-order relationship to road roughness. A slight nonlinearity is evident, and a residual acceleration exists at zero road roughness, which would be due to inputs from the on-board excitation sources. At the driver's seat, however, the vibration level is more variable with roughness, a rational consequence of the additional dynamics that come into play.

Despite the greater scatter in the relationship to the seat vibrations, a rather direct influence of road roughness is evident. Therefore, it may be predicted that truck ride vibration levels will generally increase in severity as the road system continues to deteriorate in its surface roughness condition. It may also be noted that the ISO-weighted third-octave band acceleration levels seen in the upper right-hand plots of Figures 19 and 20 are consistent with those obtained by Jex and shown in Figure 18b. While the preponderance of data points correspond to ISO permissible exposure times of three hours or more, certain road roughness conditions can cause vibrations of a severity for which the allowable exposure is barely over two hours.

Vibration Transients. Although the vibration environment within a truck is conveniently characterized by numerics which represent an average condition (e.g., RMS values and PSD's), one can hypothesize that transient motions may represent a vibration regime more significantly linked to safety. Specifically, singular road bumps, such as potholes or pavement settlements at a bridge approach, may result in high amplitude, momentary vibrations that uniquely influence the driver's ability to function as a vehicle controller.

Obtaining quantitative estimates of the momentary vibration levels typically experienced by trucks is difficult. The literature has very little to say on this topic. Jex (1981) analyzed his data to determine the mean-top-tenth and mean-bottom-tenth acceleration levels experienced

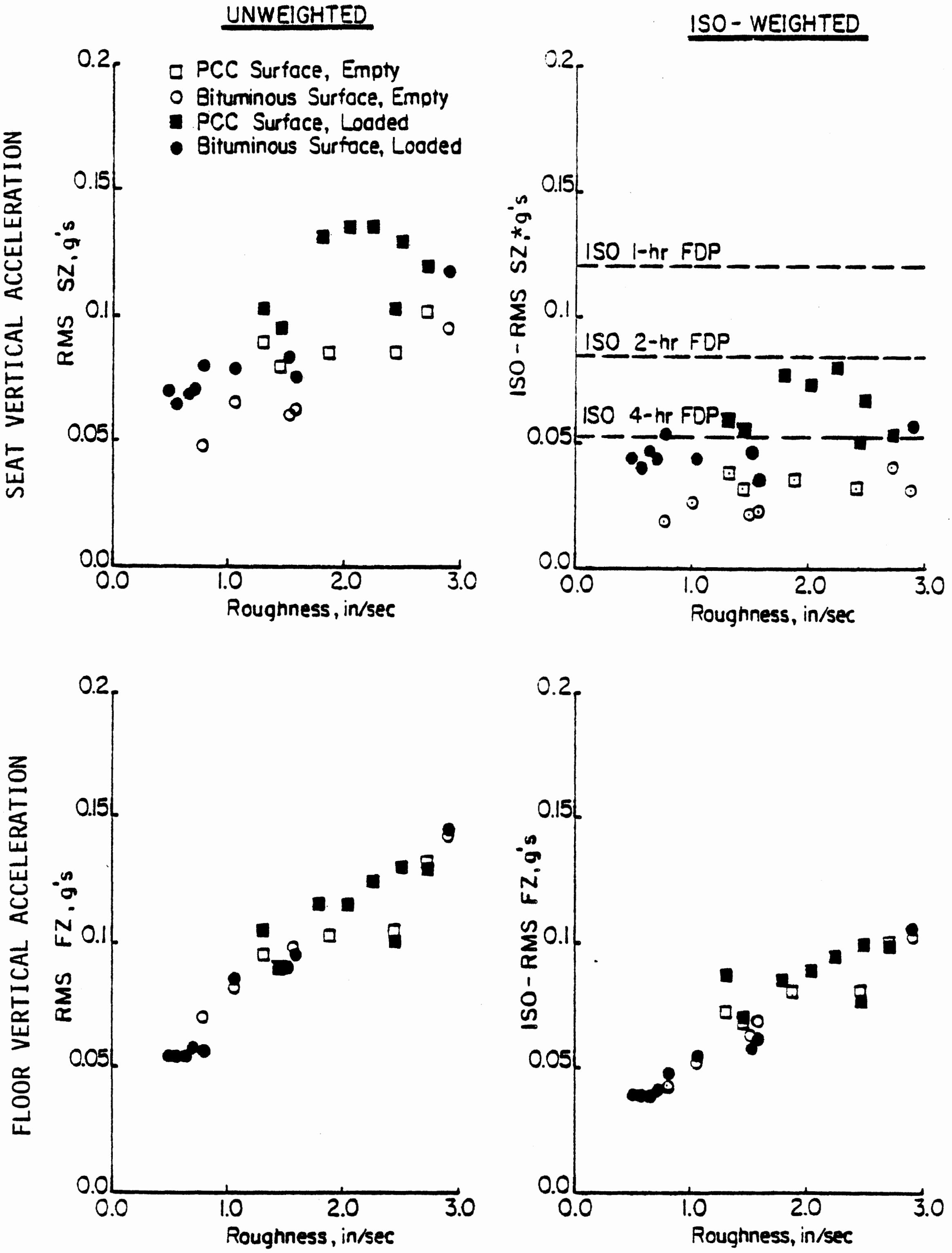


Figure 19. RMS vertical vibration levels of a truck as a function of road roughness.

*Based on a one-third octave bandwidth

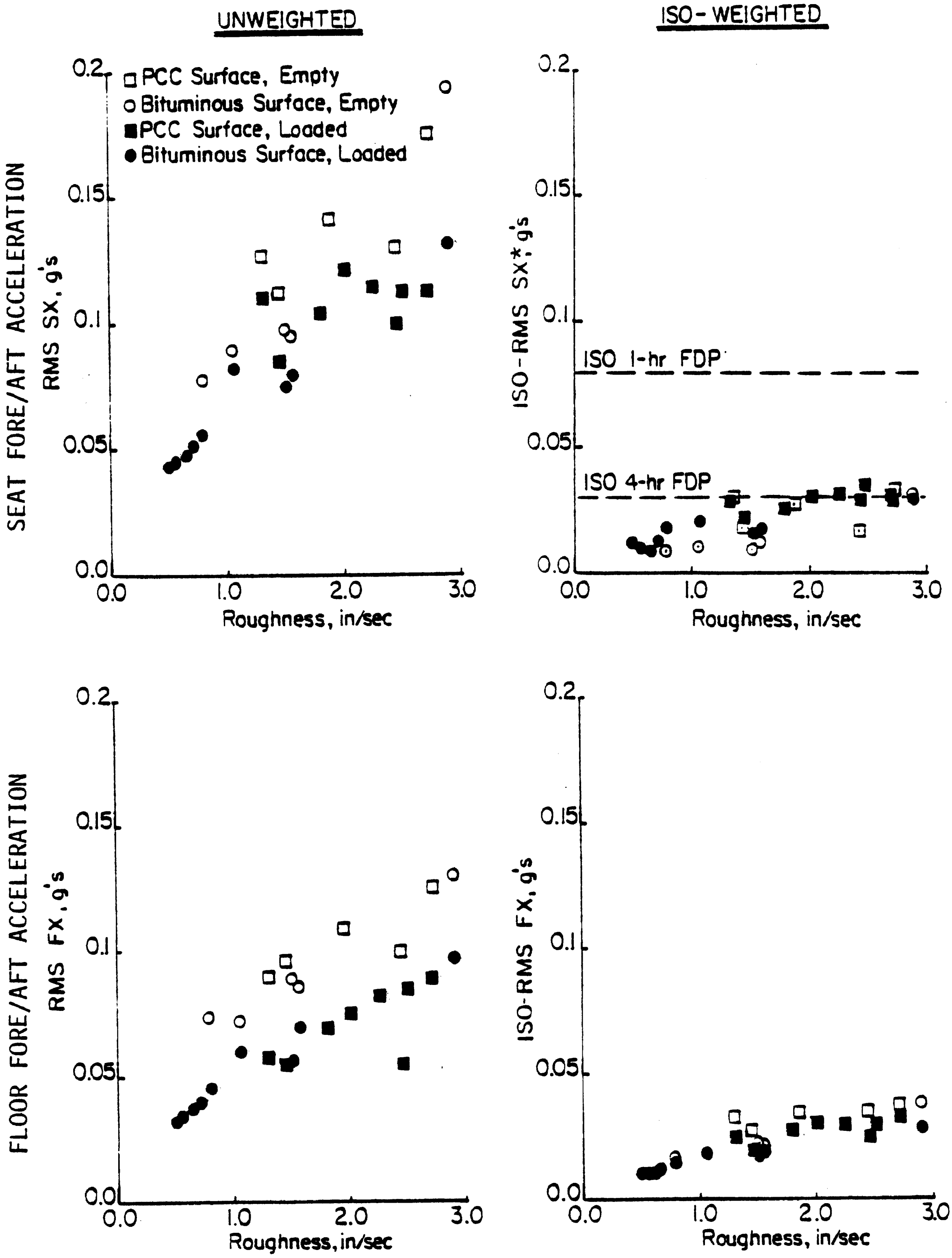


Figure 20. RMS fore/aft vibration levels of a truck as a function of road roughness.

*Based on a one-third octave bandwidth.

in his test program. (The mean-top-tenth values represent the levels of random vibration peaks which are exceeded ten percent of the time on given types of highway.) From the data that were reported, it appears that the top- and bottom-tenth percentile points are typically twice the ISO-weighted RMS levels. Thus the observed ISO-weighted RMS accelerations ranging from 0.05 to 0.13 g's, as measured for various trucks under different conditions, would correspond to a top-tenth percentile level of 0.1 to 0.25 g's. These values, however, are likely to under-estimate the maximum amplitude of the momentary vibration levels which can occur in trucks, since the test sites were purposely selected to avoid "large surface transients."

Mehta (1981) also reported data in a format which gives insight into peak momentary acceleration levels encountered in straight trucks. His histograms of truck-seat accelerations indicate peak levels on the order of 0.3 g's, both in the fore/aft and vertical directions, on a vehicle where the corresponding unweighted RMS values were 0.08 and 0.13 g's, respectively. Dupuis (1980), on the other hand, shows shock vibrations on the seat of a "truck transporting earth under heavy conditions" with peak acceleration amplitudes well over 1 g.

Even with such data, however, it is difficult to infer what consequences can befall the truck driver as the data are incomplete, given that we have no information on the frequency content. High level accelerations of well over 1 g exist at many points on a truck due to shocks and high frequency vibrations present in the chassis. Yet it is unlikely that these vibrations are of significant consequence (if momentarily transmitted to the driver) unless they contain sufficient low frequency energy to set up whole-body motions at a comparable g level. Clearly, 1 g accelerations at the seat interface at a 1-2 Hz frequency are likely to unseat the driver, complicating his control function in a much different way than would occur when a 1 g acceleration prevails at 10 or 20 Hz. As a practical example, note that small amounts of backlash in the seat mechanism can result in significant impact accelerations at the seat interface. If the data are processed so as to examine transient vibrations, these impacts may be the predominant source of high accelerations observed on the seat.

To account for the instances where drivers have reported vehicle control problems occurring as a result of (1) being unseated by a road bump or (2) impacting the travel limit of the suspension seat, it must be assumed that low frequency (1-2 Hz) accelerations on the order of 1 g or more were experienced. Obviously, these occurrences must be rare events, which depend on a coincidence of the right combination of road roughness, travel speed, and vehicle response characteristics. Being rare, these events are not commonly experienced and reported in the literature on truck ride, yet that fact should not be taken as evidence that such events cannot or do not occur.

2.3 Effects of Vibration on Man

Section 2.2 has indicated that the vibratory stimuli to which truck drivers are exposed consist of random accelerations characterized by (1) frequencies ranging from 2 to 20 Hz and (2) amplitudes ranging from 0.05 to 0.15 g RMS. Of course, vibration is not unique to the commercial truck and tractor-semitrailer. Human exposure to vibration is common is many other modes of transportation, especially in ground-supported vehicles (both military and agricultural) and rotary-wing aircraft. It is also common to a number of industrial occupations in which the operator is in contact with vibrating machinery. Because exposure to man-made vibratory environments has increased as society has become more mobile, the growing concern about adverse effects of vibration on human condition and performance has generated many studies, particularly within the last 20 years.

Basically, researchers have sought to understand the effects of vibration exposure on man's physical (biodynamic), physiological, psychological, and pathological responses, and, perhaps most importantly, on man's ability to operate equipment and controls (performance). Unfortunately, the research findings are often inconclusive, conflicting and difficult to apply to the real world. Many factors contribute to this state of affairs, including the following: differences in experimental stimuli (i.e., intensity, frequency, direction, duration, type (random or transient) and points of application); variation in subjects, their orientation and posture; and the many ways in which vibration can affect the various organs and sensory-motor systems existing in the human body. Thus, organizing, summarizing, and interpreting the literature relative to truck vibration is a difficult and challenging task.

The following discussion highlights the findings presented in the literature within the context of the vibration levels which exist in the truck cab. Overview papers prepared by key researchers in the field have been relied on heavily (viz., Shoenberger, 1972; Lewis, 1962; Guignard and King, 1972; Weaver, 1979; Shoenberger, 1970; Holland, 1966; Griffin and Lewis, 1978; Wasserman, 1979; Grether, 1971). The reference section of this report contains only those references utilized in its preparation. For a more complete bibliography on the subject of this chapter, the reader is referred to Klein, Allen, and Miller, 1980.

It appears necessary to first define some of the terminology and methods used in experiments on vibration exposure. Subsequent subsections discuss the different effects that vibration exposure can have on the human body. As illustrated in Figure 21, the immediate and direct effect of vibration is the physical or biodynamic response of the human body and its components. As a result of these mechanical responses, indirect effects may result that interact with and influence each other as well as the biodynamic response. These effects include short-term changes in physiological function, psychological state and fatigue, and perhaps long-term (chronic) pathological or health effects. These responses may, directly or indirectly, influence a person's ability to perform his assigned tasks.

2.3.1 Basic Terminology. It is important to define basic terminology that applies to experiments in vibration research. Vibration can be generally defined as a fluctuating mechanical disturbance of periodic or non-periodic nature. The simplest type of vibration is sinusoidal (or harmonic) motion at a single frequency of oscillation. This type of vibration is favored in experimental activities because responses to the amplitude and frequency of the stimulus can be clearly described and

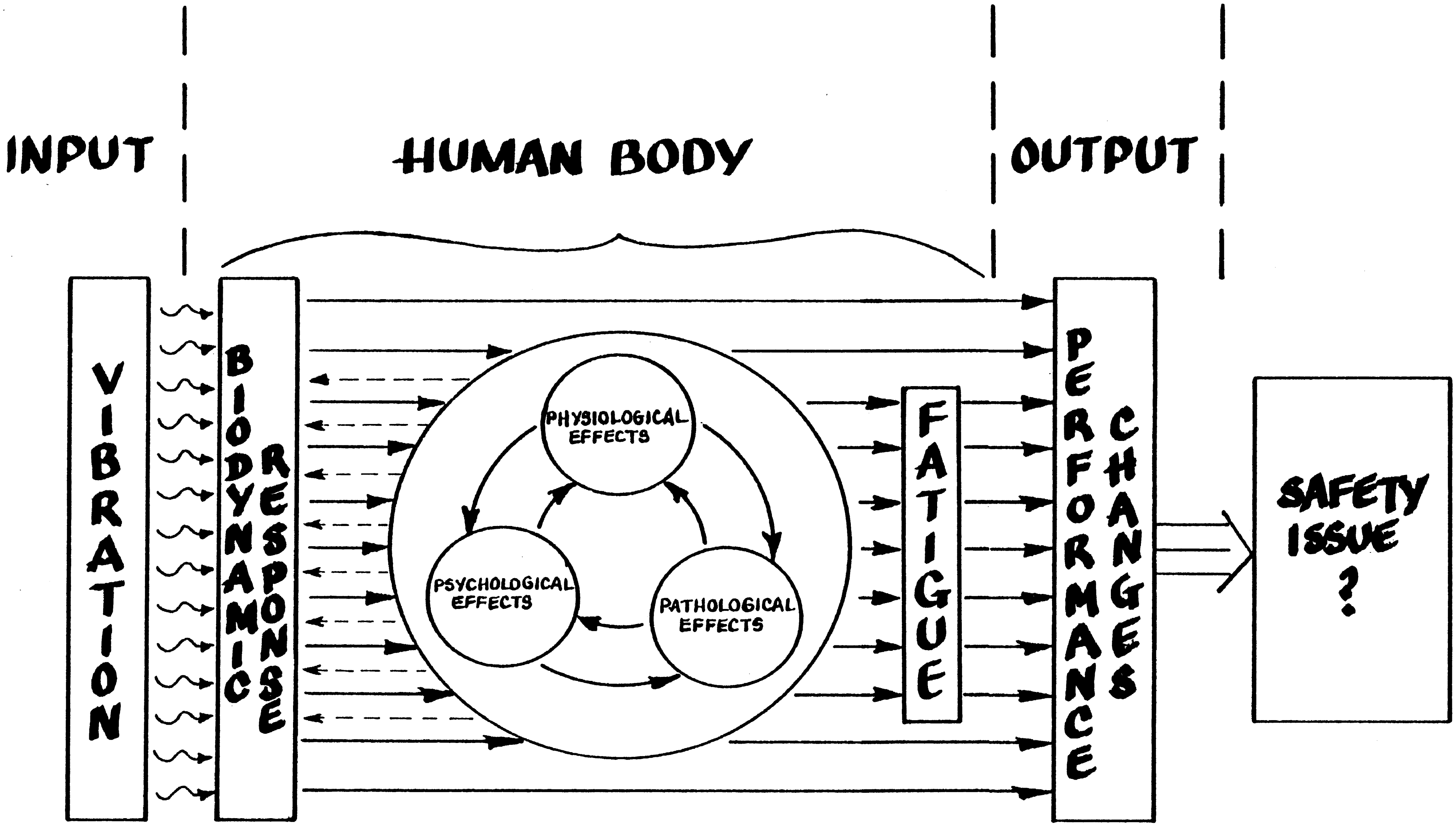


Figure 21. Schematic illustration of how vibration exposure may influence the human body and performance.

controlled. Also, the relationship between displacement and acceleration stimulus intensities are clearly defined and known (acceleration = frequency^2 × displacement). However, real-world vibrations such as those experienced in the cab of a truck are seldom periodic nor of a single frequency, but rather are non-periodic (irregular) and often transient in nature. Nevertheless, these random vibrations, over a specified period of time, can be described by complex summations of a series of sine waves having different amplitudes and frequencies as determined by Fourier analysis of the random waveform. However, the use of random, or pseudo-random, vibrational stimuli in experiments makes it difficult to establish correlations between measurements of stimulus intensity (and frequency) and human response. Experiments which use sinusoidal vibration stimuli, on the other hand, may not yield results which are meaningful in the real world.

Irrespective of whether the stimulus is periodic and sinusoidal or non-periodic and random, stimulus intensity is defined, in most instances, as the acceleration to which a subject is exposed. It is convenient to use a normalized measure of acceleration, namely, units of the earth's gravitational acceleration (where 1 g = 9.8 m/sec^2 = 32.3 ft/sec^2). For sinusoidal stimuli, the acceleration may be reported either as the peak amplitude or as a weighted level (average- or root-mean-square; RMS). In the case of random vibration, there are a number of statistics (or numerics) which can be and are used. It is also common to refer to the vibration response amplitude in reference to the stimulus amplitude by reporting the ratio of these amplitudes, defined either as the gain or the transmissibility. Stimulus amplitudes which are increased or amplified (gain greater than 1) indicate high transmissibility, while attenuations in stimulus amplitudes indicate low transmissibility.

As expected, the direction of vibrational stimuli relative to the human body is important. Different axis systems have been used to refer to the direction of these stimuli, but the most common system, as used in this report, is illustrated in Figure 22. As shown, regardless of the position of the body (e.g., sitting, standing, supine), the positive x-direction is back to front, the positive y-direction is right side to left side, and the positive z-direction is from feet to head.

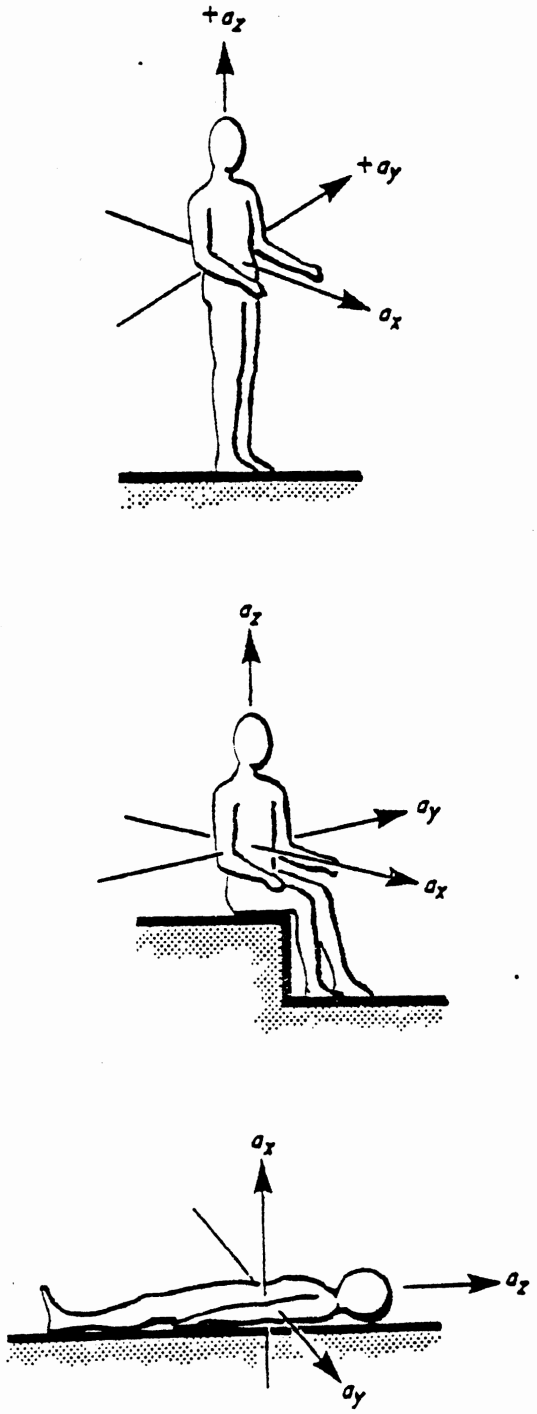


Figure 22. x, y and z axes used in vibration research (from Wasserman, et al., 1979)

2.3.2 Physical (Biodynamic) Response to Vibration. The effects of vibration on the physiology, psychology, pathology, and performance of the human subject are second order in that they derive from the vibratory displacement and accelerations of the organs, tissue, and body parts—that is, from the direct response of the human body as a complex mechanical system. Thus, an understanding of the human body's biodynamic characteristics with respect to vibrational inputs is important to understanding both short- and long-term effects on physiology and performance.

Numerous studies have attempted to (1) measure and model the human body as a mechanical system of masses, springs, and damping elements (see, for example, Figures 23 and 24), and (2) determine the transmissibility characteristics of the human mechanical system. The results depend on extrinsic factors such as the point of stimulus application, stimulus direction, stimulus intensity, and the degree of coupling to the vibrational stimulus (e.g., the use of seat belts). They also depend on intrinsic factors such as subject posture, physical build, and muscle tension.

While variations in all these factors have led to differences in experimental results, there is general agreement that when a seated subject is exposed to a vibration stimulus consisting of vertical motion of the seat, motions at frequencies between 3 and 7 Hz are transmitted to body parts with little resistance and even amplification (i.e., resonance)—that is, with vibrational inputs to the seat at 3 to 7 Hz, other parts of the body will vibrate with even greater amplitudes than the applied stimulus. The human body, then, has high transmissibility (resonant characteristics) at frequencies of vibration that are commonly found to exist at the driver's seat in a truck cab.

In experiments in which vertical vibration inputs are applied to the seat of a seated subject, head resonance is generally reported at 3 to 6 Hz and at these frequencies the head may vibrate at amplitudes of 1-1/2 to 3 times the stimulus amplitude. For lateral vibration inputs, y-axis resonances for the head, hip, and knee of seated subjects have been reported by Woods (1967) to occur at 1.5 Hz, while Goldman and

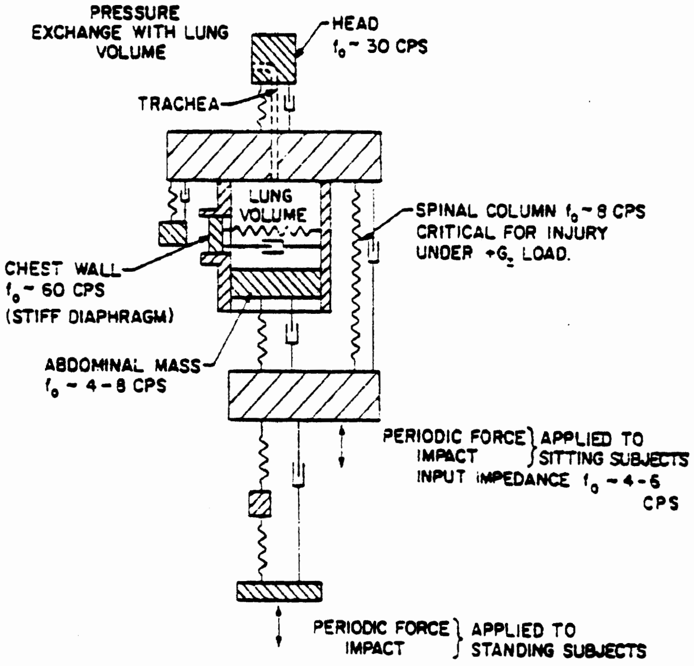
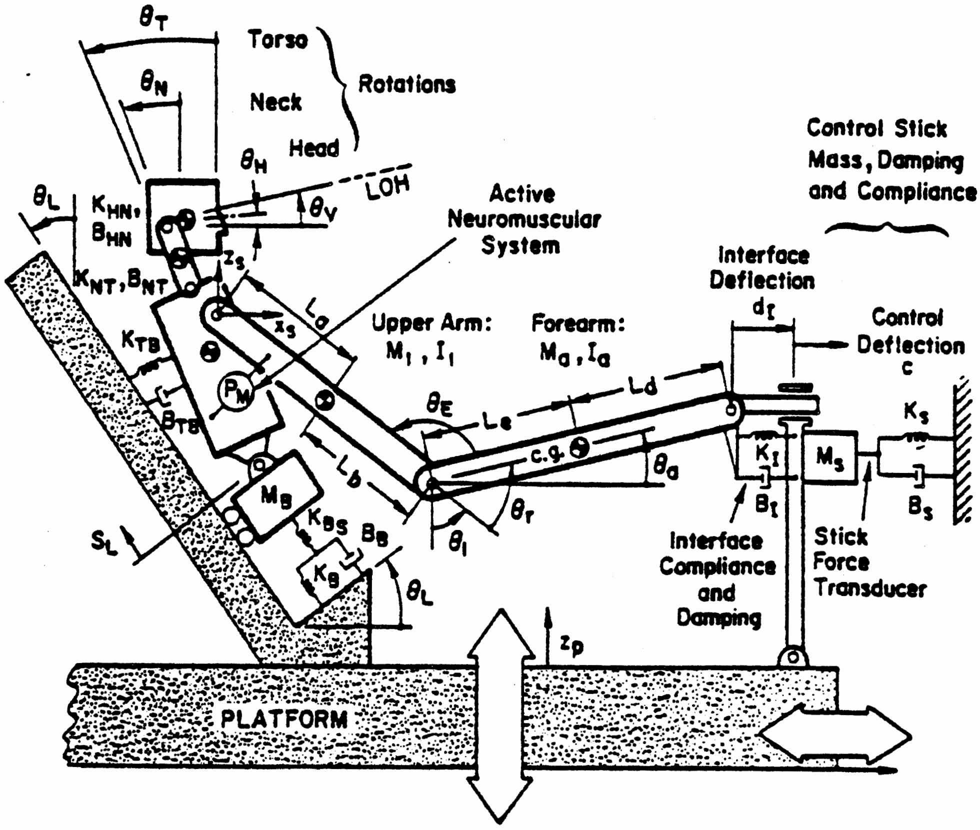
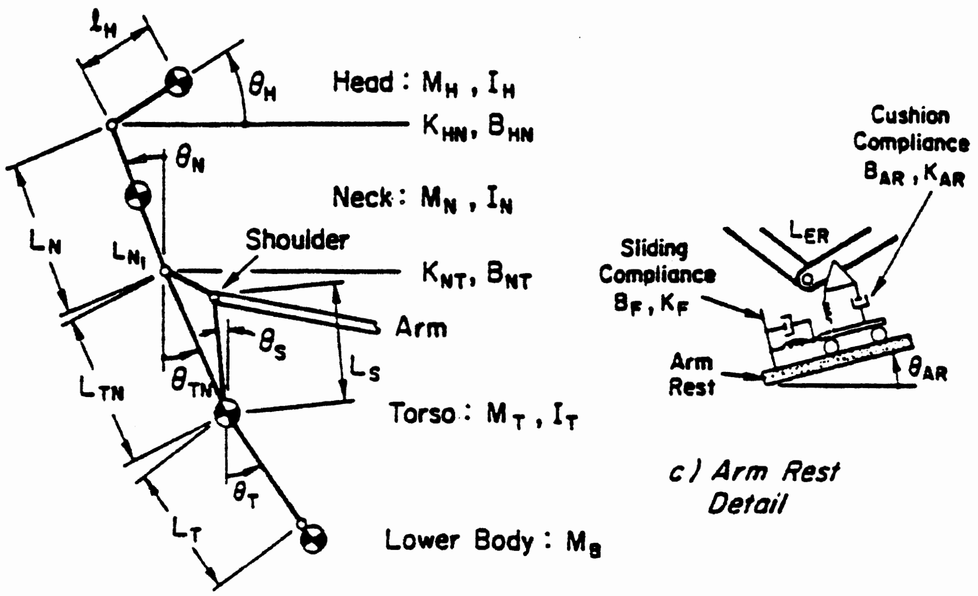


Figure 23. Mechanical model representation of human body exposed to vertical vibrations. (from Von Gierke, 1974)



a) Basic Elements



c) Arm Rest Detail

b) Body Parameters

Figure 24. Biodynamic model for studying human response and performance in vibration environments (from Jex, et al., 1979).

Von Gierke (1960) have reported fore/aft (x-axis) maximum transmissibility at the head and hip of 2 and 5 Hz, respectively.

Another pronounced resonance phenomenon is the 5 Hz natural frequency of the abdomen. At this frequency, the abdominal contents and supporting structures form a mechanically resonant system. It has also been reported that chest resonance may occur at frequencies about 1 Hz higher than the frequency range inducing abdominal resonance and that a second major body resonance in response to z-axis vibration exists at around 11 to 14 Hz, a response associated with the mechanical characteristics of the torso and spinal column.

It follows that the human body can be considered to be a complex mechanical system in which different body parts and organs are excited by stimulus frequencies in the range commonly measured in the truck cab and particularly at the truck cab seat. The human body is also a well-damped structure, however. Vibration amplification in any direction rarely exceeds a factor of three.

2.3.3 Physiological Effects of Vibration. As stated by Guignard and King (1972), physiological effects of vibration are due primarily and most directly to the differential vibratory movement or deformation of the organs and tissues of the body and secondly, and more diffusely, to stresses acting non-specifically. The primary effects tend to be frequency dependent, while the secondary effects are more dependent on the intensity and duration of the exposure. The literature contains a significant number of publications dealing with acute physiological changes induced by both mechanisms, but often the results are reported without distinction as to likely cause. A brief overview of findings is presented below for select physiological systems.

Respiratory Effects. Recent research has confirmed earlier observations that whole-body z-axis vibration at 1 to 100 Hz can result in increases in minute* respiratory volume and increased oxygen consumption. These increases are generally attributed to raised metabolic

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*Amount of air exchanged per minute.

activity due to increased activity of skeletal muscle in maintaining posture and are interpreted as being similar to that caused by physiological response to exercise. For example, (1) Zechman, et al. (1965) found increased amplitude of airflow oscillation during .5 g peak-to-peak acceleration near 5 Hz, (2) Hoover and Ashe (1962) found increases in respiratory minute volume at 8, 11, and 15 Hz for .8, 1.5, and 2.8 g intensities, respectively, and (3) Duffner, et al. (1962) found that z-axis vibration at .15, .3, and .35 g, at lower frequencies, increased oxygen consumption. In general, however, considering the intensities and periodic nature of the stimuli needed to produce measurable increases, it is doubtful that these findings have any significance to the issue of interest.

Other researchers have noted hyperventilation as a response to vibration of 1 to 10 Hz at .5 g or greater, with a maximum response at about 5 Hz indicating a connection with resonant vibration of the thorax-abdomen system. While hyperventilation has the potential for adversely affecting performance efficiency, it is again doubtful that it is significant at exposure levels common to the truck cab.

To summarize, short-term sinusoidal vibrations over the 2-10 Hz range will result in hyperventilation and increased oxygen consumption at acceleration levels above .3 to .5 g's. At lower acceleration levels, respiratory effects are small or absent and no data exist to document effects of low acceleration, long-duration, random vibration on respiratory function.

Cardiovascular Response. As with the respiratory system, changes in cardiovascular function have been observed when man and animals are exposed to whole-body vibration at infrasonic (less than 10 Hz) frequencies. However, the acceleration levels required to produce these short-term responses to regular stimuli are quite high compared to the levels sustained in the truck cab.

Hood, et al. (1966) conducted a study of humans who were subjected (in the supine position) to vertical sinusoidal vibration at frequencies ranging from 2 to 12 Hz with acceleration held fixed at .6 and 1.3 g's. These experiments indicated that cardiovascular changes were most pronounced at the 8 and 10 Hz frequencies. At the 1.2 g acceleration level, mean arterial blood pressure, heart rate, cardiac index, and oxygen consumption index rose from 20 percent to 100 percent of control values. At the .6 g acceleration level, increases in cardiovascular responses were much less pronounced. Changes in mean arterial pressure were very slight, although the cardiac index* increased from about 3.3 to 3.9. The results can be explained by a drop in peripheral vascular resistance. The increase in cardiac index was mediated through increases in both heart rate and stroke volume. Oxygen consumption also increased about 15 percent. On comparing the results from the experiments conducted at the 1.2 g and .6 g acceleration levels, it appears that 0.6 g may be near the threshold for significant effects (i.e., lower acceleration levels are not likely to elicit any shifts in cardiovascular parameters).

Interpreting the results of many studies is difficult because much of the data have been obtained in experiments conducted with animals rather than man. However, a few general statements can be made concerning the cardiovascular responses of humans to vibration. At fractional g acceleration levels, there is probably no significant effect on the cardiovascular system. The slight changes in heart rate, cardiac output, mean blood pressure, and oxygen consumption are likely to be similar to the changes produced by low level exercise. On the other hand, if there is significant periodic vibration imposed on human subjects near the frequency of the cardiac cycle, a modulation of pulse pressure could occur. However, the effect of chronic exposure to this condition has not been established for humans. Also, resonances of the blood mass oscillating in the elastic arteries could be significant, if the frequency of the vibratory input is near any of the resonant frequencies.

Muscle Activity and Postural Mechanisms. Dupuis (1974) found increased electromyograph (EMG) activity occurring in the postural muscles as a result of vibratory input from a tractor. Increased muscle activity may be the result of a vestibular or proprioceptive reflex which tries

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*Cardiac index is defined as the cardiac output in liters per minute per square meter of body surface (L/min/m^2).

to maintain body position through contraction of the proper muscle groups (this hypothesis would apply more to vibration along the x and y axes). Increased muscle activity may also result from the tonic vibratory reflex (TVR) which causes muscle tendons to stretch in response to vibration. Through special receptors in the tendons, a spinal reflex is initiated to contract the muscles in a way that tends to restore the initial position of the tendon or attached limb. In other words, a continual periodic stretching of the muscle as caused by vibration can result in contractions of the muscle at the vibration frequency.

These muscular contractions are believed to lead to muscle fatigue and, indeed, this factor has generally been accounted for in the development of the fatigue-decreased-proficiency boundary as exists in ISO Standard #2631 (ISO, 1978). Poulton (1978) has suggested, however, that the muscle tension induced by vibration may not always be harmful and that at a frequency of 5 Hz (corresponding to maximal resonance of the human body), increased muscle tension results in increased vigilance which is beneficial to performance. As illustrated in Figure 25, the increased muscle tension occurring at 5 Hz is explained by noting that muscle tension reduces shoulder vibration at this frequency, but increases shoulder vibration at other frequencies. Presumably, the tendency is to tense up when the vibration stimulus is in the vicinity of 5 Hz, an act which increases vigilance, and to relax at the lower and higher frequencies, which presumably decreases vigilance. Although the short-term effect of muscle tension may be increased vigilance and alertness, the long-term effect may be increased fatigue much as would result from a long period of mild exercise.

Ocular-Motor System (Visual Acuity). There are basically two sensory inputs to the ocular muscles that provide visual acuity during body (head) motion or when a subject is engaged in tracking moving objects. The pursuit reflex is essentially a visual feedback system whereby retinal information is used to track moving targets with the head fixed or track fixed targets when the head rotates. The vestibular-ocular reflex utilizes head motion information transmitted from vestibular

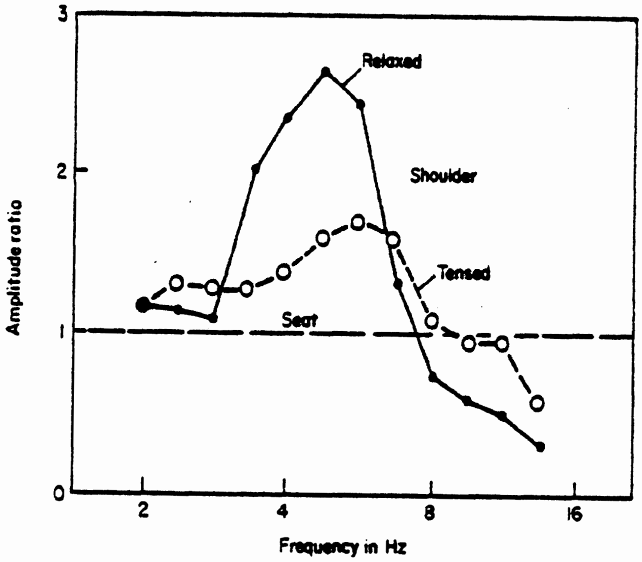


Figure 25. Effect of muscle tension on amplitude of shoulder vibrations (after Guignard, 1965).

receptors of the inner ear to extra-ocular motor neurons controlling eye muscle contraction, and thereby enhances the ability of the eyes to fix on non-moving targets when the head is moving.

It has been established by a number of researchers that the pursuit reflex breaks down at oscillation frequencies above 1 Hz (approximately) or when the angular velocity of the target exceeds 50 deg/sec. Neurophysiological studies with monkeys (Fernandez and Goldberg, 1971) and visual acuity experiments with human subjects have shown that the vestibular system provides the necessary information for compensatory eye movements in the frequency range of 1-10 Hz where the pursuit reflex is ineffective.

For the situation in the truck cab where the head may move with frequencies generally less than 10 Hz, it seems clear that the person with normal vestibular function will have little or no difficulty performing visual tasks with respect to non-moving objects outside the cab. However, since the pursuit reflex does not provide for visual image stabilization much above 1 Hz, truckers with reduced or no vestibular function may have difficulties in reading signs and extracting other information from the roadway.

For image stabilization within the cab, the situation is more complex. With the head moving, vestibular information is transmitted to the extra-ocular muscles attempting to move the eyes to compensate for this movement. But, since the cab interior is also moving (differently than the head itself), these vestibular signals are, in fact, inappropriate and must be suppressed for good visual acuity. Barnes and Benson (1977) have found that the breakdown in suppression of vestibular information has gain/frequency characteristics similar to those of the pursuit reflex, suggesting that it is the pursuit reflex which suppresses inappropriate vestibular signals. This means, however, that inappropriate vestibular information above 2 Hz cannot be adequately suppressed. If the truck driver's head experiences oscillations at a frequency of 2 Hz or above, visual acuity for reading similarly moving panel displays will be decreased because of inappropriate eye movements generated by the vestibular system. In addition, if the displays are oscillating above 2 Hz either out of phase with or at different frequencies or amplitudes from the driver's head, the pursuit reflex would not be adequate to provide image stabilization even without the inappropriate vestibular signals. It is, therefore, likely that when the truck driver's head experiences oscillations of significant magnitude above 2 Hz, the ability to read panel-mounted gauges may be seriously decreased.

2.3.4 Psychological Effects.

Subjective Responses. A major portion of the experimental data that has been collected to define the response of the human operator to vibration relies on the subjective reactions of subjects and workers to experimental and real-world environments. There has been considerable criticism of studies which collect these types of results, both because of the lack of an objective measurement terminology (e.g., use of terms like "annoying," "discomfort," "painful"), and a lack of sufficient human factors input in the design of the experiments.

One attempt at describing human subjective response to short-term vibration exposures was compiled by Goldman utilizing the results of Ziegenruecker and Magid (1959). The results show the greatest sensitivity and least tolerance in the range of 4 to 8 Hz, as illustrated in Figure 26. Barton and Hefner (1976) and others (Sandover, 1979 and Dupuis, 1975) have shown that vibration levels of normal ambulation (walking) exceed those levels of exposure found in typical earth-moving machinery. Yet, the subjective response in ambulation is one of unperceptable vibration, while the subjective response to vibration in earth movers is that the vibration level is high. While it is pointed out that man may have an instinctive tolerance to vibration inputs to the foot, this paradox illustrates the problem of working with subjective response data.

While caution must be used in applying these data to any given situation, due to the subjective nature of the experiments from which they were derived and a multitude of other associated problems (e.g., the boundaries may shift up or down depending on the particular situation

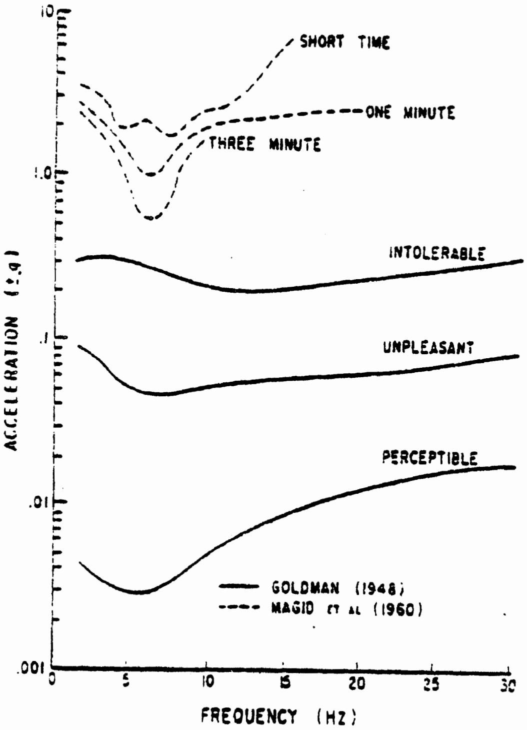


Figure 26. Goldman's composite subjective response curves and z-axis voluntary tolerance curves of Magid, et al, 1960 (after Chaney, 1964 and Shoenberger, 1972).

and type of personnel involved—Von Gierke, 1975), they can nevertheless serve as a useful reference for assessing the severity of the vibration environment within the truck cab. Given the results outlined in the previous section, the Goldman plot suggests that the truck environment may be within the subjective range of "unpleasant."

Stress Effects. In addition to the conscious subjective responses, psychological stress (irrespective of driver or subject awareness) is often implicated as a significant consequence of exposure to vibration. A number of studies in which subjects have been exposed to vibration levels found within trucks and rotorcraft have sought to measure this stress through a number of indicators such as:

1) increase in heart rate
2) increase or decrease in blood pressure
3) increase or decrease in hormone levels
4) development of ulcers or gastric upset.

In general, results show no significant evidence for vibration causing stress reactions (McCutcheon, 1974; Mackie, 1974; Hornick, 1966; Grether, 1972). In fact, driving or riding as a passenger in an automobile appears to elicit more significant cardiovascular responses from the average driver than have been found due to mechanical circumstances within the truck cab (Simonson, 1968).

The possible synergistic effects of heat, noise, and vibration have also been investigated with somewhat conflicting results. Grether (1971 and 1972) and Mackie (1974) found no significant changes when these stressors were present concurrently. Guignard (1979) cites evidence for increased hormone levels among industrial workers (not truck drivers) exposed to noise and vibration. Mackie (1974) found that the rate of adrenalin production while driving was above normal resting levels no matter what the truck cab environment. It may well be that the alertness and concentration necessary to keep a truck safely on the road far outweighs any input from a mechanical standpoint.

Simulated heat and vibration stresses well above the range encountered in the truck cab environment have been investigated in aerospace research. Winters (1963) found decreases in 17-OH steriod excretion and an increase in catacholamine excretion in monkeys, but the changes were not significant enough to clearly indicate physical or emotional stress levels. Megel (1962) hypothesized that the kidney weight increase observed in rats under high heat and vibrational conditions may have been due to stress-induced release of antidiuretic hormone (ADH). At best, this is circumstantial evidence for stress reactions and it occurred under heat and vibration conditions generally exceeding that of the truck driver's environment.

2.3.5 Pathological Effects. Pathological effects due to whole-body vibration are generally classified into two categories—acute and chronic. Acute effects are the painful and injurious results of short-term exposure to intense levels of vibrational stimuli. They are associated with vibration magnitudes well in excess of 4 or 5 g's and thus acute effects are not an issue in the context of driving a truck. Chronic effects, on the other hand, involve the issue of whether long-term health problems result from repeated exposure to moderate, but not immediately damaging, levels of vibration.

Milby (1974) pointed out that the long-term health question requires consideration of both cause-effect mechanisms and statistical associations:

> "...the finding of a positive relationship between exposure and morbidity experience is termed an association and cannot be attributed to a cause and effect relationship without the eventual specification of a mechanism of action. The literature of epidemiology includes classic examples of strong associations which subsequently turned out to be spurious in nature. To reiterate, even the strongest statistical association cannot be considered proof of causation."

There is no known cause-effect mechanism at the vibration levels of trucks and heavy equipment. Such vibration levels are less than those of natural activities such as walking. Dupuis (1976) measured typical vertical vibration levels of 0.55 g's RMS at the hip and 0.39 g's RMS at the head of walking subjects. Simic (1970) measured similar vertical vibration levels on walking subjects, and also showed that the fore/aft and side-to-side vibration levels at the lumbar spine were 65 to 81 percent and 37 to 48 percent, respectively, of the vertical levels. Barton (1976, 1981) analyzed vertical vibration from walking according to the ISO methods and, although the levels were lower than those reported by Dupuis and Simic, the results exceeded measured levels on heavy equipment. Dupuis, Simic, and Barton, each with a different format, all showed peak values, or shocks, in the range of 0.5 to 1.0 g's with each walking step.

In view of the fact that vehicle vibration levels were well below those of the natural activities replaced by vehicles, Guignard (1970) hypothesized that externally imposed whole-body vibration somehow affects human organs differently than does self-generated vibration. No evidence nor theory has been developed to date to support the hypothesis. A few authors have hypothesized that whole-body vibration acts as a generalized stress. The previous section in this report stated that there is no significant evidence of vibration causing stress reactions. From the long-term aspect, Smith (1978) showed that farm laborers (tractor driving) and heavy equipment operators, both occupations with regular exposure to vibration levels higher than those of trucks, had a significantly lower than average incidence of stress-related diseases (coronary heart and artery disease, hypertension, ulcers, and nervous disorders). Thus, to date there has not been developed a theory of a cause-effect mechanism whereby prolonged exposure to truck vibration would lead to long-term health problems.

Similarly, the literature does not provide persuasive evidence of a statistical association between health problems and prolonged occupational exposure to whole-body vibration. Table 1 summarizes the findings of some of the better known studies. One or another investigation points to possible associations between vibration and certain health problems such as peptic ulcers, appendicitis, vertebrogenic pain, and diseases of the male genitalia. However, the discrepant pattern suggests that other occupational factors may be involved, including dietary habits of long-distance drivers, handling of cargo and baggage, etc. Further,

Table 1. Selected Epidemiological Studies and Results.

Date	Author(s)	Occupational Condition	Med. Condition(s) Studied	Conclusion(s)
1960	Rosegger, Rosegger	Agricultural Tractors	Cardiovascular	No problems reported.
			Urinary	No problems reported.
			Gastrointestinal	No control group. Had 37 volunteers from institute. Problems correlate to eating habits.
			Musculoskeletal	No control group. Comparisons to other data were in error (misrepresented?). No evidence that the findings were anything other than normal aging processes.
1972	Dupuis, Christ	Agricultural Tractors	Musculoskeletal	No control group. Data is similar to that for other occupations.
				No association between back problems and hours per year of tractor driving.
				Only one-half of subjects were exclusively full-time farmers; one-third were part-time farmers with another occupation dominant or were not farmers at all.
1974	Milby, Spear	Off-Road Heavy Equipment	All Body Systems	"With the exception of the male genital organs (prostatitis), there is no persuasive evidence for the existence of increased age adjusted mobidity rates among men exposed to whole-body vibration over the control population (on-site non-operators) when experience is not taken into account. Further, on the basis of these data there appear to be no disease conditions for which the standardized morbidity ratio tends to increase continually with exposure to whole-body vibration."

Table 1. Selected Epidemiological Studies and Results (Cont.)

Date	Author(s)	Occupational Condition	Med. Condition(s) Studied	Conclusion(s)
				The authors hypothesized on the existence of a selection process whereby afflicted operators would leave the occupation. See results of follow-up study to test the hypothesis.
1974-1976	Spear, et al.	Off-Road Heavy Equipment	Follow-Up of Above Study for:	Purpose was to test the selection hypothesis for the disease conditions in which such a selection process was suspected.
			Ischemic Heart Disease	Result was of interest, but not statistically significant.
			Other Metabolic Disease	Hypothesis was rejected.
			Other Bone and Joint Diseases	Result was not statistically significant.
			Male Genital Disease	Hypothesis was decisively rejected. The results suggest instead that the relevant finding for this disease in the first study was a spurious finding. One or two false positive findings were expected in the first study at the significance level used. A third hypothesis was suggested, that exposed persons develop disease at an earlier age. However, after the first two hypotheses were rejected by the first two studies, the third hypothesis was not tested.
1975	Kelsey, Hardy	Automobile Drivers	Acute Herniated Disc	The "relative risk" for any male driver of an automobile was 2.67, except for small cars, in which case the relative risk was less than 1 (i.e., small cars are protective).

Table 1. Selected Epidemiological Studies and Results (Cont.)

Date	Author(s)	Occupational Condition	Med. Condition(s) Studied	Conclusion(s)
		Truck Drivers	Acute Herniated Disc	From a study of 19 truck drivers, the "relative risk" was 4.67. If former truck drivers were included, the "relative risk" was 2.86. From a study of 31 truck drivers, the "relative risk" was 2.26. If former truck drivers were included, the "relative risk" was 1.59. The "relative risk" values given were selected by the author from several possible values available in the data. The selection process was inconsistent, which suggests the author was diligent in not overlooking any possibility of missing a finding of interest. Note that only one of the four values reported was substantially larger than the value for automobile drivers, and that two values were somewhat lower.
1976	Gruber, Ziperman	Bus Drivers	Ischemic Heart Disease	Not significant.
			Essential Hypertension	Not significant.
			Varicose Veins (Varicocele)	Not significant.
			Hemorrhoids	Not significant.
			Respiratory System	Not significant.
			Peptic Ulcer	Significant.
			Appendicitis	Significant.
			Diverticulitis, Colitis, Gastroenteritis or Anal Disease	Not significant.
			Kidney or Ureter	Not significant.
			Male Genitalia	Not significant.
			Skin and Tissue	Not significant.
			Inguinal Hernia	Not significant.
			Displaced Discs	Not significant.
			Ankylosis of Spine	Not significant.
			Vertebrogenic Pain	Not significant.

Table 1. Selected Epidemiological Studies and Results (Cont.)

Date	Author(s)	Occupational Condition	Med. Condition(s) Studied	Conclusion(s)
1976	Gruber	Interstate Truck Drivers	Obesity	No association.
			Nervous Stomach	Frequency associated with physiological responses to sustained psychosocial stress.
			Hypertension	Matter-of-degree disorder; excess of condition probably artifact of selection by medical examiners.
			Hemorrhoids	Slightly more than bus drivers, same as control group.
			Hypotension	Matter-of-degree disorder; excess of condition probably due to selection of medical examiners.
			Peptic Ulcer	Vibration may be a factor; irregular dietary habits; mode of living, lack of physical activity, psychosocial stress, alcohol, caffeine, nicotine.
			Kidney Disease	Not significant
			Diseases of male genitalia	Less than control group, same as bus drivers.
			Pilonidal Cyst	Not significant.
			Vertebrogenic Pain Syndrome	Significant.
			Bone Deformities (Congenital Kyphosis, Scoliosis)	Significant.
			Sprains, Strains (Wrists, Ankles, Knees, Back, etc.)	Significant

as Milby and Spear (1974) point out, a certain number of false positive findings can be expected simply by chance in a given epidemiological study, even in the absence of any exposure-related causation. Thus, the studies to date are notably lacking in providing persuasive evidence of a pattern of health problems related to truck ride quality. Of particular interest is that the trend of the data is suggestive that persons exposed to occupational whole-body vibration have less kidney problems than non-exposed persons.

At the present time, then, there is no hard evidence that whole-body vibration related to truck ride is a factor in causing health problems which, in turn, might affect the highway safety of trucks. Yet, while truck vibration cannot generally be linked to health problems as a causative factor, it may be a factor (though not proven) in aggravating and promoting existing diseases and health problems. Thus, for truck drivers with certain health problems (regardless of cause), poor truck ride quality could be a factor in reducing driving effectiveness and attentiveness and thereby reduce truck safety.

2.3.6 Performance Changes Due to Vibration Exposure.

General. Whereas the biodynamic, physiological, pathological, and psychological effects of vibration exposure may be important phenomena with respect to driver health, their importance to motor carrier safety lies only in the extent to which these phenomena cause changes or decrements in the ability of a driver to perform his or her driving task. As indicated earlier, human performance can be directly affected by the biodynamic response of the human body to vibration and may be less directly affected by the physiological, pathological, and psychological stresses that may result from these biodynamic responses.

There have been many efforts, in the past 20 years or so, to study the effects of vibration exposure on human performance. Most of these studies have been motivated by a concern with the vibration levels encountered in military vehicles and generally have exposed subjects to sinusoidal stimuli of varied intensity, frequency, and duration along the z-axis. There have also been some studies involving vibration in the x- and y-axis directions, multi-dimensional vibrations, and random or pseudo-random vibrations with multiple frequency components. As with other studies concerned with the effects of vibration on man, a multitude of techniques, experimental conditions, and types of investigations have been used and the results are often in conflict, with considerable disagreement existing. It is not the purpose here to bring all of these results into focus on the truck ride process, but rather to highlight some of the more general observations.

There are three basic levels at which external stimuli-like vibration may affect performance. These are: (1) afferent or sensory interferences, (2) central nervous system interference, and (3) efferent or motor control interference. At the sensory level, the primary concern has been that of visual acuity and a number of studies have attempted to investigate vibration effects on visual performance. In assessing the performance of the central nervous system, reaction time measurements and perceptual judgment tasks (choice reaction time) have been commonly used. Motor control performance has been investigated by asking subjects to perform compensatory tracking tasks (which also involve sensory and central nervous system performance) and, less frequently, other types of motor control tasks.

Visual Acuity. There is a general consensus in the literature that exposure to whole-body vibration at frequencies ranging from 1 to 25 Hz can result in significant loss of ability to stabilize images of objects fixed in space. The loss of visual acuity is related to the magnitude of oscillation in this frequency range and is also sensitive to other factors such as the type of vibration, subject posture, display illumination levels, viewing distance, and the degree of coupling of the subject to the stimulus. The findings are consistent with knowledge about the role of the vestibulo-ocular system in compensatory eye movement for head movement and, given that truck cab seat vibration frequencies fall mainly within 2-10 Hz, it would seem that loss of visual acuity for objects outside the cab (i.e., stationary and distant objects) is not a serious problem.

There are relatively few studies dealing with vibratory effects on visual acuity in the case of objects which are moving along with the subject. As previously discussed, the vestibulo-ocular system does not deal adequately with this situation and the limits of the pursuit system to suppress the vestibular reflex or track the targets above 2 Hz probably result in decreased visual acuity at frequencies below 10 Hz. It has also been reported by Guignard and Irving (1962) that the decrement in visual acuity for fixed targets was largest for frequencies of 3.5 Hz (for a stimulus frequency range of 2-10 Hz) when targets were near the eyes. The implication is that large amplitude oscillations due to whole-body resonance effects resulted in the greatest visual acuity decrement due to limits in compensatory eye movements.

Reaction Time and Perceptual Judgment. Reaction time experiments, with and without perceptual judgment (i.e., choice), are generally considered to be measures of central, rather than peripheral or sensory, neural processes. Beginning with Coermann in 1938, a number of experiments have been conducted to assess the effects of vibration on central nervous system function using both sinusoidal and random vibrations. While some minor decrements in performance have been noted (Shoenberger, 1970; Hornick, 1962), these decrements have been found for vibration stimuli well above the typical levels of vibration that exist in the cab of a truck (i.e., above .35 peak g). For the most part, there is fairly substantial evidence (and agreement) that the central nervous function and tasks dependent on it are highly resistant to performance decrements during whole-body vibration in the .5 to 10 Hz range (Grether, 1971).

Tracking and Other Motor Tasks. Two-dimensional compensatory tracking tasks have been the most common experimental tool used to assess changes in human performance due to environmental stress factors such as vibration. Specific task requirements vary but, in general, the subject is requested to control the position of a cursor on a visual display with respect to another moving or stationary target or region, using hand or foot controls. The control dynamics are important and may be varied between tests or within a test to increase or decrease task difficulty. The ability to perform these tracking tasks depends both on motor performance skills and visual acuity, and decrements in either or both can lead to decrements in performance (i.e., increases in the tracking error).

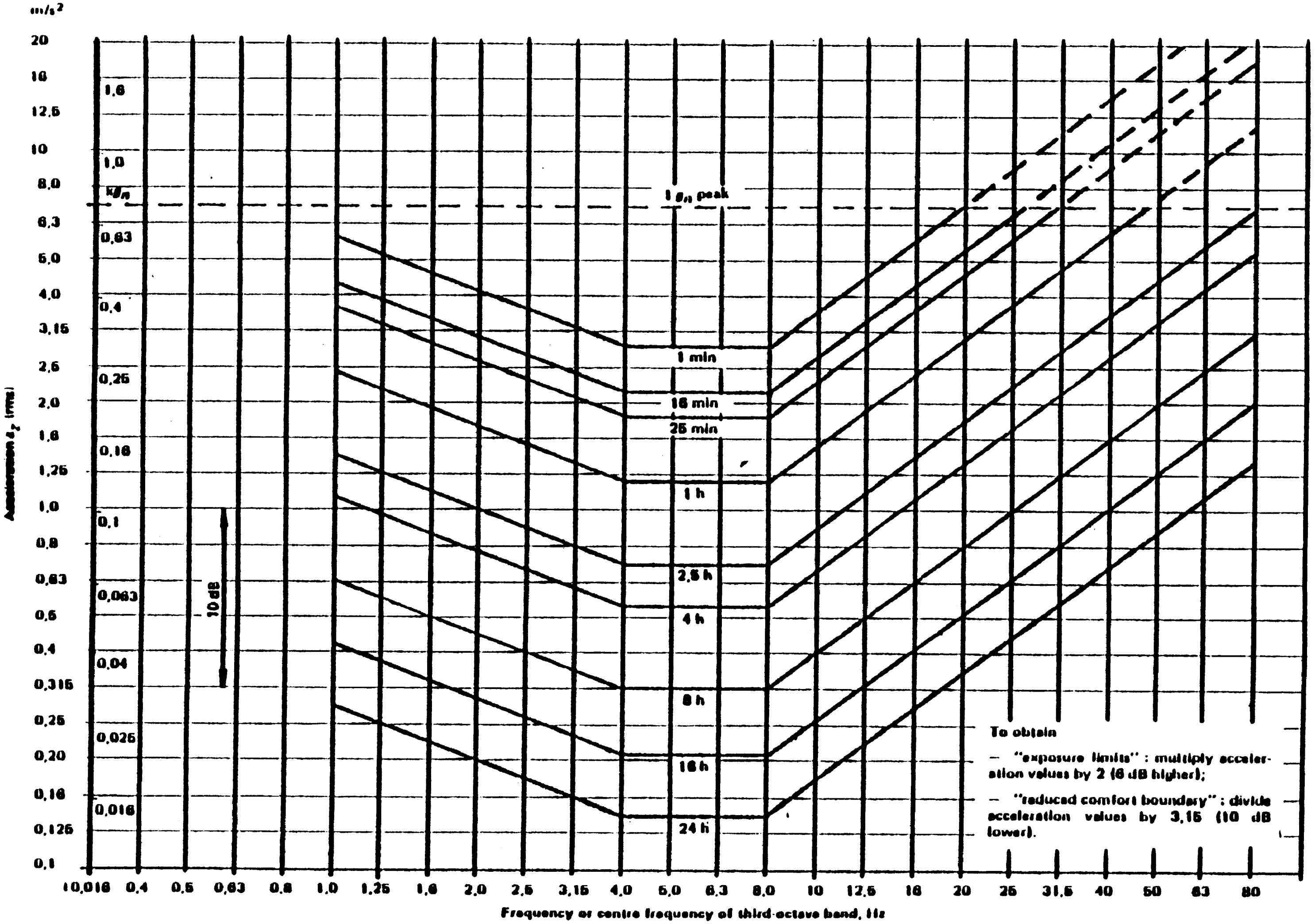
Most tracking experiments performed to elucidate the effects of vibration have used sinusoidal stimuli covering a range of frequencies, amplitudes, and exposures. However, a limited number of tests have also been made using random stimuli with a limited bandwidth. Most studies have involved z-axis vibration but subjects have also been exposed to x- and y-axis vibrations.

Collins (1973), Grether (1971), and others have attempted to summarize the results of tracking experiments conducted in the presence of vibrational stimuli. While much of the work has been criticized (Guignard and Kim, 1972) as (1) being of "poor quality" and (2) using a "diverse methodlogy" which leads to confusion, there is substantial evidence that z-axis vibration adversely affects a person's ability to perform tracking tasks. Noticeable increases in tracking error have been found in the range of 2 to 16 Hz (especially around 4 Hz) for seat acceleration amplitudes of .05 g RMS and up in the z-axis direction. Vibration inputs along the x and y axes have also been found to interfere with performance at these levels, with the largest performance decrements occurring at 1.5 to 2 Hz. These findings, along with the fact that the degree of decrement is often proportional to vibration amplitude, suggest that mechanical interference (at hand or eye) is primarily responsible for the observed decrements in performance. Additional factors supporting this conclusion are the observations that tracking decrements tend to be greatest in the direction of the vibrational stimuli, and that support and restraint devices for the arm significantly reduce the effects of vibration.

Since most experiments have utilized sinusoidal stimuli, there is concern over whether these results are applicable to the real world in which random vibration prevails. However, Weisz, et al. (1965) and Parks (1961) both used three types of stimuli (sinusoidal, sinusoidal with random amplitude, and a true random process) and found no difference in the effects produced by any of the three types.

A lesser number of studies have utilized other types of motor control tasks to study effects of vibration. Loeb (1955) used tests of mirror tracing, tapping speed, manual steadiness, and hand grip and found only steadiness to be decremented. Schmitz (1959) studied hand tremor, body sway, foot pressure, and foot reaction time and found only foot pressure to be significantly decremented. Chaney and Parks (1964), using vertical vibration between 1 and 27 Hz, found increased errors in using controls for adjusting meters, and Guignard and Irving (1960) found decrements in the precise positioning of markers. Most recently, Gauthier, et al. (1981) found significant decrements in position, velocity, and force control for 18 Hz, .1 g vertical vibration and concluded that alterations in proprioceptive information from muscle sensory receptors is responsible.

2.3.7 Standards for Human Exposure to Whole-Body Vibration. As has been seen from the literature, the potential consequences of human exposure to vibration cover a broad range of effects, extending from (a) simple concerns for comfort, to (b) the ability to perform work tasks, to (c) the risks of endangering health or safety. The national and international standards organizations have responded to the need for guidance in this area and have developed guides for evaluating human exposure to whole-body vibration. The most widely recognized of these are the International Standard ISO-2631 (ISO, 1978) and the American adaptation ANSI S3.18 (ANSI, 1979). These standards reflect the best consensus on the knowledge to date as to human tolerance to vibration. The standards define boundaries for exposure to vibration as a function of intensity, frequency, duration, and direction. Figures 27 and 28 show the limits for longitudinal and transverse vibration known as the Fatigue-Decreased Proficiency (FDP) boundary. Quoting from the Standard, the FDP boundary "....specifies a limit beyond which exposure to vibration can be regarded as carrying a significant risk of impaired working efficiency in many kinds of tasks, particularly those in which time-dependent effects ("fatigue") are known to worsen performance as, for example, in vehicle driving." Guidelines are also suggested for an Exposure Limit (i.e.,

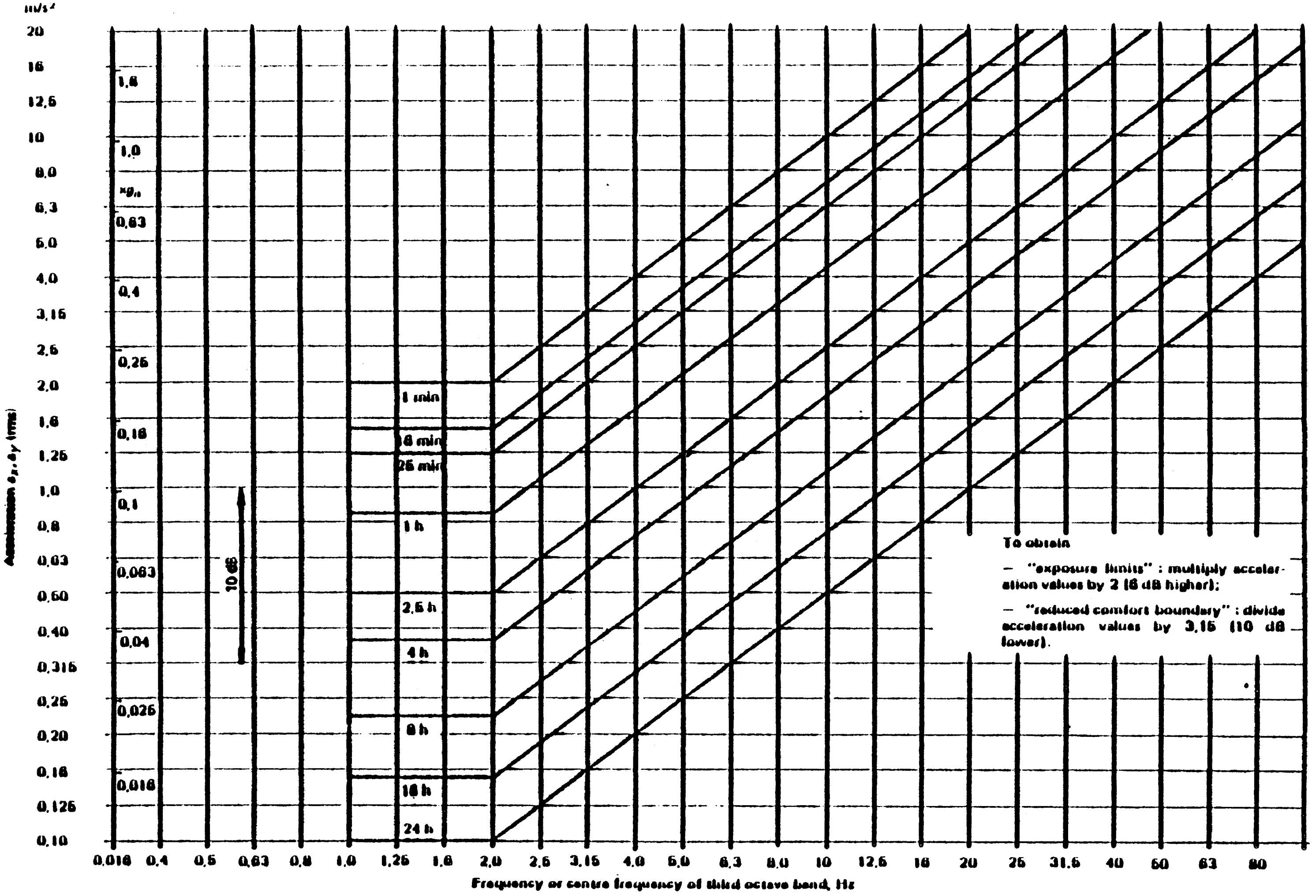


To obtain

– "exposure limits" : multiply acceleration values by 2 (6 dB higher);

– "reduced comfort boundary" : divide acceleration values by 3,15 (10 dB lower).

Figure 27. International Standard 2631. Longitudinal (a_z) acceleration limits as a function of frequency and exposure time; "fatigue-decreased proficiency boundary."



To obtain

– "exposure limits" : multiply acceleration values by 2 (6 dB higher);

– "reduced comfort boundary" : divide acceleration values by 3,15 (10 dB lower).

Figure 28. International Standard 2631. Transverse (a_x, a_y) acceleration limits as a function of frequency and exposure time; "fatigue-decreased proficiency boundary."

for preservation of health or safety) and a Reduced Comfort Boundary (i.e., for preservation of comfort). The limits take the same form as the FDP boundary, being increased by a factor of two in the first case, and reduced to one-third the FDP level in the second case.

The standards define a specific method by which the vibration spectrum is to be evaluated against the suggested boundary. For broad-band vibration such as occurs with trucks, "...the RMS value of the acceleration in each (one-third octave) band is to be evaluated separately with respect to the appropriate limit at the centre frequency of that band." This is the method of choice in that it is sensitive to vibration concentrated in narrow bands that may have specific influence on the human body.

In addition, a weighted overall acceleration method of evaluation is also allowed as an approximation by which to simplify measurement and characterize the vibration by a single quantity. By this method the overall spectrum is weighted in accordance with the limits shown in Figures 27 and 28 to yield an ISO-weighted RMS for the total spectrum. The RMS for the whole spectrum will, in general, exceed that of a one-third octave band; hence, the method is conservative in that the evaluation will indicate vibration conditions worse than they really are. An appropriate adjustment for this error would be to increase the exposure criteria by a factor somewhere between one and four, depending on the vibration spectrum. It is on this basis that Von Gierke has recommended an adjustment factor of 1.7 when using the weighted overall acceleration method to evaluate truck ride (Von Gierke, 1982). Nevertheless, in cases where this method results in impermissible levels of vibrations, the standards recommend resorting to the detailed method based on third-octave band frequency analysis.

In general, the ISO and ANSI standards indicate that a truck driver who experiences third-octave band vertical vibration intensities of 0.056 g's RMS in the 4-8 Hz range would be in a "reduced comfort" condition after a short time interval and would experience decreased proficiency after four hours of exposure. Further, at the level of 0.12 g's RMS, the driver would experience an immediate "reduced comfort" condition leading to decreased proficiency within a one-hour period. It also must be considered that the standard guide assumes daily routine exposure, five days per week. Less frequent exposure might favor acceptance of slightly higher levels.

2.3.8 Summary. The human body is a complex biodynamic system which responds to vibratory inputs in many ways, depending on the location and direction of the applied stimulus. Examination of the available evidence suggests that the vibration stimuli which commonly exist in the cab of heavy goods vehicles are likely to cause:

1) little or no effect on physiological function of the cardiovascular and respiratory systems,
2) a tendency to increase muscle tension, especially at frequencies near 5 Hz,
3) little effect on visual acuity with respect to fixed objects at a distance,
4) a degradation of visual acuity with respect to (a) objects moving with the subject's head or (b) fixed objects near the eyes,
5) a subjective rating of "unpleasant" or "uncomfortable" (in some situations), but no measurable change in mental stress,
6) increased fatigue after significant and continuous periods of exposure, similar to that resulting from mild exercise,
7) possible increase in subjective symptoms of certain pathological disorders, such as spinal problems, after repeated exposures over a period of years,
8) no measurable direct effects on reaction time or intellectual processes (e.g., CNS function), and
9) measurable decrements in compensatory tracking task performance, steadiness tasks, foot pressure control, and other fine-motor control tasks.

Many of these findings have been obtained in laboratory settings which bear little, if any, relationship to the real-world process of driving a truck. Consequently, Klein (1980) and his associates have recommended that the effects of vehicle vibration upon driver performance be investigated by requiring driver subjects "to perform real-world tasks ... under very tightly controlled traffic and vibration scenarios." Arnberg and Astrom (1979) did, in fact, use a driving simulator to examine the influence of road roughness on the "tiredness" and performance of drivers engaged in control of a passenger car. In these experiments, 30 subjects were exposed to random vibrations at levels corresponding to the two-hour Fatigue-Decreased-Proficiency boundary defined in ISO 2631. Arnberg concluded that this vibration level (as induced by road roughness in a passenger car) does affect a driver's performance and "alertness," both during the period when vibration is being experienced and afterwards. Again, the key question is whether these observations, as derived from a simulator experiment, hold in the real world and whether, in fact, the observed changes in driver performance and behavior are significant factors relative to the accident causation process.

2.4 Does Ride Vibration Contribute to the Accident Frequency of Trucks and Tractor-Trailers?

The discussion in the preceding section has attempted to characterize the truck ride environment, and draw from the literature on the effects of vibration on man, to determine in what ways the driver's biodynamic state may be altered by the presence of vibration. The ultimate objective, however, is to look for vibration effects on safety as measured by accident frequency. Since the accident record lacks information which would define the vibration levels present in an accident-involved truck, alternative methods must be used for correlating vibration with accident frequency. The alternative chosen here is to hypothesize the possible ways in which vibration could impact on performance of the driver/vehicle system and look for associated effects in the accident record. It should be noted that these mechanisms, as listed below, are hypothesized as ways in which truck vibration could increase the potential for accidents simply for the purpose of guiding the analysis of accident data. However, only the results from that analysis can infer whether these mechanisms are potentially significant. Further, it should be recognized that this process cannot assess the potentially positive influences that truck vibration could have on accident prevention.

The first possible way that the truck ride vibration environment can lead to decrements in driving performance of consequence to motor carrier safety is due to the blurring of images in the rear-view mirror. Loss of visual acuity, in this instance, is probably most severe when the mirror vibrates at higher frequencies than the driver's head (i.e., the object moves and the head doesn't), in which case the visual pursuit reflex is completely inadequate for image stabilization. It may also occur as a result of inappropriate vestibular compensation, if the mirror is moving with the head. In any case, the decrease in image clarity could possibly lead to errors in perceiving a passing vehicle or in deciding when to merge back into a lane after passing. At a minimum, it would increase the time required to look in the mirror (i.e., look away from the traffic ahead), and this interruption could be a factor in accident causation, especially in heavy traffic. A decrement in the ability to see images clearly in the rear-view mirror would be especially significant at dawn or dusk when headlights are possibly turned off and during wet weather when visual acuity is already decreased and glare and road surface reflection add to the problem of image clarity.

A second way in which vibration may lead to performance decrements of significance to safety is the possible increase in fatigue experienced after a long period (e.g., four hours or more) of driving. Such fatigue appears to be caused mainly by the increased muscle tension required to maintain a seated position and reduce head and shoulder vibration, or because of tonic reflex stimulation through muscle spindle receptors in the muscles themselves. Presumably, fatigue would lead to decreased vigilance and alertness, resulting in delayed or inappropriate responses to emergency situations. On the other hand, the muscle tension response to vibration may act to prevent sleep and this result would be a positive factor. The increased vigilance or alertness due to vibration-induced muscle tension has been previously noted and, presumably, is a positive factor, prior to fatigue setting in.

In this regard, it should be noted that much of the evidence for vibration-induced fatigue comes from diverse experiments in which the data are primarily subjective in nature. Given the lack of objective data defining the increase in fatigue caused by vibration, per se, it may be that the normal demands of driving a truck are far more important to the fatigue process (McDonald, 1979).

McDonald (1979) has reviewed the fatigue research which has been conducted over the past 40 years or so and concludes that this research provides little insight into the true nature and causes of fatigue, particularly as occurs in the occupation of driving a truck. He submits that the actual task of driving a truck is not particularly demanding and that driving for long periods is not sufficient, per se, to cause a significant deterioration in the driving function. Rather, he argues that the typical truck driver is stressed in many ways. For example, besides the exposure to a vibratory environment and the long hours of work, there is the problem of working at night or on alternating shifts, the uncomfortable physical conditions (e.g., high noise levels), the schedule pressure, and so on, all of which, in combination with bad weather, congested traffic, or monotonous driving conditions, can lead to deterioration in (a) decision making, (b) risk taking, and (c) general courtesy to other road users, as well as to drowsiness and inattentiveness.

A third way in which vibration can lead to an increased potential for an accident event is the large amplitude oscillation or bump which jars a driver from his seat and therefore from a position of control. Such an event is likely to be an infrequent occurrence and would only be safety related if the driver were executing a maneuver (e.g., a sharp turn or an emergency stop), or if the road conditions were such as to require constant and careful attention to the control process.

A fourth way in which vibration may lead to performance decrements on the part of the driver is the morbidity that might occur or be aggravated with long-term exposure to vibration. If a truck driver suffers from physical ailments such as low back pain or gastrointestinal disorders (regardless of the initial cause), truck vibration may aggravate the symptoms and disease severity. The resulting discomfort may lead to increased stress, fatigue, distraction, and perhaps to seated positions which could reduce driving effectiveness.

A fifth way in which vibration could lead to an increased potential for truck accidents derives from the influence of vibration on a driver's ability to manipulate the steering, braking, and throttle controls on the vehicle. The practice of using laboratory tracking tasks to measure the influence of vibration on the ability of a human operator to perform a control function implies that the investigator believes that these laboratory findings have relevance to the real-world tasks of controlling a truck and resolving traffic conflicts. However, there is no direct evidence to support this assumption. There is, however, some anecdotal evidence to suggest that the vibration experienced in a truck cab can interfere with the ability of the driver to modulate the brake pedal when making an emergency stop on a rough section of roadway.

Although not involving the driver directly and thereby not justifying the term "ride," a sixth way in which vibrations, per se, can influence the accident record derives from the vertical response of the running gear to the disturbance created by the uneven road surface. To the extent that the tires lose contact with the road surface, the ability of the truck to "hold the road" will be degraded. In other words, steering and braking performance will suffer irrespective of what control actions are taken by the driver, other than the significant action of selecting a speed which will reduce the disturbance created by the road. Not only is there very little analytical and experimental research addressing the dynamics of the "road-holding" phenomenon (as occurs in heavy goods vehicles), there is little evidence to indicate the importance of the "road-holding" process to the accident record.

Given that the literature can be interpreted to suggest several possible vibration mechanisms (as identified above) that may contribute to the accident record, it follows that some attempt should be made to determine whether the accident record can be interpreted to shed light on any, or all, of the identified paths by which the safety of motor carrier operations may be influenced by truck ride quality. At present, it appears that no such studies have ever been made. Consequently, an effort is made below to review existing information on the use and accident experience of one specific segment of the motor carrier fleet, namely, the combination vehicle which consists of a truck tractor hauling a semitrailer. First, data on the national population of tractor-trailer combinations and their use in motor carrier operations are summarized, followed by an overview of their accident experience. Inasmuch as 1978 is the latest year for which state accident records are available, truck usage and accident data for the same time period are used throughout most of the analysis. Subsequent to this overview, an effort is made to interpret the data with respect to the possible impact of ride vibration on accident involvement.

2.4.1 Tractor-Trailer Combinations in the U.S.: Their Numbers and Use. In 1978,* the Federal Highway Administration (FHWA) reported that there were about 1,400,000 combination vehcles registered in the United States. These vehicles accounted for 0.9 percent of all vehicles registered that year. The FHWA also estimated that these combination vehicles traveled about 67 billion miles in 1978, or about 4.3 percent of the mileage accumulated by the total vehicle population. (Combination vehicles with straight trucks as power units are included in these figures.) The estimated average annual mileage driven per combination vehicle is 50,000 miles (FHWA, 1978).

Descriptive information on the national population of trucks is provided by the Truck Inventory and Use (TIU) Survey conducted in 1977 by the Bureau of the Census as part of the Census of Transportation. Descriptive statistics on the various types of combinations and their use have recently been prepared from the TIU Survey by Campbell, et al. (1981).

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*In 1980, the latest year for which FHWA data is available, the estimated combination vehicle mileage decreased to 60 billion miles (4.0 percent of the total vehicle mileage), resulting in estimated average annual mileage for combination vehicles of 42,705 miles.

Table 2 shows the distribution of tractor combinations in 1977 by operator classification. Also shown is the average annual mileage of vehicles in each of the operator classifications and the percentage of the total annual vehicle mileage accumulated by tractor combinations in each classification. It is observed that private carriers are the largest single group, operating 47 percent of the tractor combinations and accumulating 38 percent of the total mileage. The common and contract carriers taken together are referred to as ICC "authorized" carriers and operate 32 percent of the tractor combinations which accumulate 43 percent of the total mileage. The differences in the proportions of vehicles and total mileage for these two groups arises from the difference in average annual mileage reported in the survey for the vehicles in the two groups. Tractor combinations operated by authorized carriers had an average annual mileage of 65,000, while the combination vehicles operated by private carriers had an average annual mileage of about 40,000.

Table 3 shows the distribution of tractor combinations by fleet size. Fleet size is defined by the TIU Survey as the number of tractors operated from the same "base of operation," namely, the locality in which the tractor is based. Almost one-fourth of the tractors are in "fleets" that have only one tractor at a given base of operation. These carriers are typically characterized as "owner-operators." Tractors in larger fleets tend to have higher average annual mileage than tractors in smaller fleets. About 15 percent of the tractors are in fleets of 50 or more. These fleets accumulate 22 percent of all combination vehicle miles.

Tractors can be described as "cabover" (cab-over-engine) or "conventional" (cab-behind-engine) and refinements thereof. Table 4 shows the distribution of tractors in the United States by cab style. Cab-forward and cabover tractors constitute 43 percent of all tractors and accumulate 54 percent of all tractor miles. The cabover tractors are more frequently used in long-haul service and have higher average annual mileages, as indicated in Table 4.

The distribution of tractors by cab style is probably the most pertinent descriptive information available with regard to ride vibration issues. Cab styles are listed in Table 4 in order of increasing

Table 2. Distribution of the Number and Mileage of Tractor Combinations by Operator Classification.

1977 TIU SURVEY

Operator Classification	Estimated Vehicles		Average Annual Mileage	Percent of Total Miles
	Number	Percent		
Private	389,189	47.4	39,433	37.9
For Hire				
Common	183,296	22.3	64,836	29.4
Contract	81,812	10.0	66,594	13.5
Exempt	43,428	5.3	71,755	7.7
Intrastate	107,380	13.1	35,371	9.4
Daily Rent	14,522	1.8	56,392	2.0
Unknown	1,303	0.2	50,393	0.2
Total	821,113*	100.0	49,310	100.0

*The version of the TIU file currently being used by the FHWA for the Highway Cost Allocation Study estimates that in 1977 there were 1,082,000 tractor-trailer combinations in the contiguous 48 states.

Source: Campbell, et al. (1981)

Table 3. Distribution of the Number and Mileage of Tractor Combinations by Fleet Size*.

1977 TIU Survey

Fleet Size	Estimated Vehicles		Average Annual Mileage	Percent of Total Miles
	Number	Percent		
1	199,269	24.3	42,544	20.9
2-5	177,983	21.7	41,141	18.1
6-10	92,228	11.2	47,384	10.8
11-20	89,412	10.9	50,780	11.2
21-50	103,851	12.6	58,771	15.1
51-100	61,041	7.4	64,624	9.7
100+	64,690	7.9	76,649	12.2
Unknown	32,507	4.0	23,408	1.9
Total	821,113	100.0	49,310	100.0

*Number of tractors operated from the same "base of operation."

Source: Campbell, et al. (1981)

Table 4. Distribution of the Number and Mileage of Tractor Combinations by Cab Style.

1977 TIU Survey

Cab Style	Estimated Vehicles		Average Annual Mileage	Percent of Total Miles
	Number	Percent		
Cab Forward	30,703	3.7	29,070	2.2
Cabover	319,994	39.0	65,861	52.1
Short Conventional	144,488	17.6	35,632	12.7
Medium Conventional	179,996	21.9	36,895	16.4
Long Conventional	142,111	17.3	46,392	16.3
Other & Unknown	3,638	0.5	--	0.3
Total	821,113	100.0	49,310	100.0

Source: Campbell, et al. (1981

wheelbase length. Vehicles with a shorter wheelbase generally produce a more severe ride as compared to those with a longer wheelbase. Table 4 illustrates the extensive use of cabover tractors in high mileage service where the long-term effects of ride vibration are most likely to be relevant.

Table 5 is derived from survey responses which described the trailer unit most frequently used with a given tractor. Vans, as a group, are the most frequently used type of trailer and account for nearly 48 percent of the reported trailer units. Platform trailers are hauled most frequently by 25 percent of the tractor owners, followed by tank trailers at 10 percent. The tractors which most frequently pull van trailers accumulate 58 percent of the total mileage. Tractors used to haul auto transport and tank trailers also have higher average annual mileages than tractors which most frequently pull other types of trailers.

2.4.2 Overview of Combination Vehicle Accident Experience. The Fatal Accident Reporting System (FARS) operated by the National Highway Traffic Safety Administration (NHTSA) collects uniform data on all police-reported motor vehicle traffic fatalities in the United States. The accident experience of combination vehicles during calendar years 1975-1979 has been extracted from the FARS data by O'Day, et al. (1980). In 1978,* 4,231 combination vehicles were involved in fatal accidents in the United States. (Bobtail tractors are included in these figures.) Combination vehicles constituted 6.5 percent of all vehicles involved in fatal accidents in that year. The fatalities included 971 occupants of heavy trucks, constituting 20 percent of the total number of fatalities in accidents involving combination vehicles (4,746). In turn, the number of fatalities in accidents involving combination vehicles constituted 9.4 percent of all motor vehicle traffic fatalities in 1978. In other words, fatal accidents involving combination vehicles have more fatalities per accident than fatal accidents not involving combination vehicles.

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*In 1980, the number of combination vehicles involved in fatal accidents decreased to 3,897, with reduction in total fatalities to 4,409, constituting 8.6 percent of all motor vehicle traffic fatalities.

Table 5. Distribution of the Number and Mileage of Tractor Combinations by Trailer Body Style.

Trailer Body Style	Estimated Vehicles		Average Annual Mileage	Percent of Total Miles
	Number	Percent		
Platform w/Devices	19,107	2.3	32,978	1.6
Low Boy	49,538	6.0	20,742	2.5
Other Platform	137,846	16.8	42,190	14.4
Cattle Rack	16,086	2.0	54,402	2.2
Insulated Nonrefrig. Van	26,465	3.2	61,040	4.0
Insulated Refrig. Van	58,460	7.1	73,947	10.7
Furniture Van	32,184	3.9	46,251	3.7
Open Top Van	13,897	1.7	51,187	1.8
Other Enclosed Vans	260,806	31.8	55,191	35.6
Beverage	7,122	0.9	24,235	0.4
Utility/Mobile Service	980	0.1	13,094	---
Winch or Crane	9,967	1.2	20,001	0.5
Wrecker	477	0.1	30,263	---
Pole or Logging	29,159	3.6	36,774	2.6
Auto Transport	11,814	1.4	63,207	1.8
Boat Transport	946	0.1	36,214	0.1
Mobile Home Pullers	6,495	0.8	26,358	0.4
Garbage Hauler	1,847	0.2	33,424	0.1
Dump	49,752	6.1	44,942	5.5
Tank/Liquids	66,050	8.0	58,391	9.5
Tank/Dry	16,601	2.0	59,851	2.5
Concrete Mixer	1,783	0.2	10,761	0.1
Other	3,548	0.4	2,820	---
Unknown	87	0.0	---	---
Total	821,113*	100.0	49,310	100.0

Source: Campbell et al. (1981)

The number of combination vehicles involved in fatal accidents in the United States increased at a rate of about 12 percent per year over the period 1975-1978. Over this same period, combination vehicle mileage, as reported by the FHWA, increased about 7 percent per year. Passenger car mileage increased about 4 percent per year during this period. In 1979, the increase in combination vehicle mileage and fatal accident involvement leveled off, and preliminary information indicates that for 1980 the mileaged decreased 11 percent while fatal accidents decreased by 16 percent.

A breakdown of fatal accidents by collision type is given in Table 6. About 27 percent of the fatal accidents involving combination vehicles are seen to be single-vehicle accidents, which, in this table only, includes accidents involving pedestrians. Note that angle (or intersection-type) collisions are the most common type of collisions which produce fatalities. Also shown in this table is the percentage of all fatal accidents involving combination vehicles in each type of collision. For example, 3.9 percent of all fatal single-vehicle accidents in 1978 involved combination vehicles. Overall, 8.9 percent of all fatal accidents involved a combination vehicle. Percentages falling above or below this overall figure for any particular subgroup indicate that combination vehicles are involved in proportionally more or less accidents in that subgroup as compared to all other vehicles (principally passenger cars). Thus, Table 6 indicates that combination vehicles are involved in proportionately fewer single-vehicle fatal accidents and proportionately more of all the remaining categories which involve more than one vehicle. This finding may be taken as a reflection of a higher probability of fatality in a multiple-vehicle accident when one of the vehicles is a combination vehicle.

The distribution of combination vehicle fatal accidents by road class is shown in Table 7. The majority of these accidents (62.6 percent) occur on U.S. and state routes that are not limited access. Only 23.6 percent of the fatal accidents involving combination vehicles occur on Interstate and other limited-access roads. Again, combination vehicle fatal accidents occur more frequently on rural roads as compared to fatal accidents not involving combination vehicles. This finding is probably

Table 6. Distribution of Fatal Accidents by Collision Type.

Collision Type	Combination Vehicle Fatal Accidents		Percent of All Fatal Accidents for Each Collision Type
	Number	Percent	
Single Vehicle	1075	26.9	3.9
Rear-end	621	15.5	29.6
Head-on	778	19.5	12.9
Rear-to-rear	10	0.3	50.0
Angle	1202	30.1	15.4
Sideswipe	305	7.5	35.8
Unknown	8	0.2	10.8
Total	3999	100.0	8.9

Source: O'Day, et al. (1980)

Table 7. Distribution of Fatal Accidents by Road Type.

Road Class	Combination Vehicle Fatal Accidents		Percent of All Fatal Accidents for Each Road Class
	Number	Percent	
Interstate	901	22.5	23.0
Other limited access	45	1.1	8.3
Other U.S. route	1217	30.4	17.1
Other state route	1288	32.2	8.8
Other major artery	56	1.4	5.1
County road	187	4.7	2.6
Local street	239	6.0	2.7
Other road	20	0.5	2.2
Unknown road class	46	1.2	6.2
Total	3999	100.0	8.9

Source: O'Day, et al. (1980)

a reflection of the difference in the use of combination vehicles as compared to other vehicles. Statistics gathered by the FHWA for 1978 indicate that combination vehicles accumulate about 81 percent of their mileage on rural roads, while passenger cars accumulate about 42 percent of their mileage on rural roads (FHWA, 1978).

The FARS data provide a relatively complete enumeration and description of fatal accidents at the national level. However, only a small percentage of all accidents are severe enough to produce fatal injuries. Clearly, information on injury and property-damage-only accidents is needed to complete the accident picture. However, the only other national data source on heavy truck accidents are the reports submitted by carriers to the Bureau of Motor Carrier Safety (BMCS). These accident reports are filed by interstate carriers for all accidents, involving their vehicles which result in death, injury requiring treatment away from the scene of the accident, or 2,000 or more dollars of property damage. Authorized carriers are the major group reporting to the BMCS.

An examination of the BMCS data for 1978 yields the number of fatal, injury, and property-damage involvements shown in Table 8. Combination vehicles in single-vehicle accidents are shown separately from combination vehicles involved in all other types of collisions. Single-vehicle involvements comprise 35.8 percent of the total number of accidents that are reported. Property-damage-only involvements have a higher proportion of single-vehicle involvements, while the accidents involving injuries and fatalities have higher proportions of multiple-vehicle collisions.

Not all carriers that operate combination vehicles report accidents to BMCS. Consequently, the number of injury accidents reported to the BMCS is not the national total for combination vehicles. However, a rough approximation of such a national total may be obtained by inflating the number of injury involvements reported to BMCS for authorized carriers by the ratio of the combination vehicle fatal involvements reported by FARS to the combination vehicle fatal involvements reported to BMCS. The number of fatal involvements reported to BMCS is 38.3 percent of the fatal involvements reported by FARS. This figure is

Table 8. Fatal, Injury, and Property Damage Involvements by Collision Type: Combination Vehicles Operated by Authorized Carriers.

1978 BMCS

Accident Severity	Collision Type				Total	
	Single Vehicle		Other			
	Number	Percent	Number	Percent	Number	Percent
Property Damage*	4678	53.7	4027	46.3	8705	100.0
Injury	3817	27.0	10304	73.0	14121	100.0
Fatal	268	16.5	1353	83.5	1621	100.0
Total	8763	35.8	15684	64.2	24447	100.0

*The BMCS reporting threshold is $2,000 property damage or more.

reasonably consistent with the percentage of combination vehicle mileage accrued by the authorized carriers, namely, 42.9 percent, as shown in Table 2. On adjusting the BMCS data by this ratio of fatal involvements, a national estimate of approximately 36,900 injury involvements is obtained.

To supplement the data on fatal and injury-producing accidents, files of police-reported accidents in the States of Michigan, Pennsylvania, Texas, and Washington (as maintained at HSRI) have been examined to estimate a national total of injury and property-damage accidents as would be reported by the police in all of the 48 contiguous states. Without recounting the details of this exercise, it can be stated that approximately 200,000 combination vehicles are involved in police-reported accidents annually. About 2.2 percent of these involvements produce fatal injuries and another 32 percent produce non-fatal injuries. The majority of the injuries (fatal and non-fatal) are received by occupants of the other vehicle (usually passenger cars) in multiple-vehicle collisions. The majority of these involvements occur on rural roads. The available descriptive information on the accident involvement of combination vehicles is consistent with their extensive use in long-haul service, as indicated in the exposure data.

2.4.3 Evidence of the Effects of Ride Quality on Accident Involvement. This section reviews the most pertinent computerized accident files publicly available in the U.S. to see of existing data provide any evidence to support the hypothesized mechanisms relating ride vibrations to highway safety. In general, the causes of accidents are not well understood. This situation arises from the fact that any accident has more than one causative factor, and these factors interact in complex ways. Accidents are rare events and, strictly speaking, each one is unique. Efforts to identify the effect of any specific factor are confounded by superimposed effects and interactions of other factors. Statistical techniques provide an analytical means to cope with problems of this nature. However, statistical results can be misleading unless the findings are coupled with independent knowledge of the mechanisms operating.

As a means of addressing this issue with limited resources, the accident files were interrogated to identify the prevalence of the factors of interest. Factors that are infrequently associated with accidents generally will not merit attention as much as factors that are frequently associated with accidents. For the purposes of this review, the pertinent question is whether existing accident data provide significant evidence to support the hypothesized mechanisms relating ride vibrations and highway safety. The finding of such evidence would support the need for further study. The finding of no evidence would not necessarily imply that ride vibrations do not influence highway safety, but only that existing data do not support the hypothesized mechanisms. If the true mechanisms are very complex, they may require complex analytical techniques and detailed data to reveal them. With this perspective, the following material presents the available data on the incidence of specific factors suggested by the hypothesized mechanisms.

One of the possible short-term influences of vibration on driver performance (identified earlier) is degraded rear vision due to vibration of rear-view mirrors. One might hypothesize that such a problem might be evidenced in passing maneuvers, either in seeing a passing vehicle, or in merging in front of a passed vehicles. The available accident data do not have sufficient detail to identify these specific situations. However, passing (including improper passing) is indicated as a contributing factor in less than one percent of the police-reported accidents involving combination vehicles in Texas and Washington. (The passing vehicle, car or truck, is not identified.) Thus, the available data do not identify any significant classes of accidents where mirror vibrations may be relevant.

Earlier, it was suggested that the vibration environment in the tractor cab might, on the one hand, produce decrements in motor control and, on the other hand, displace the driver from the controls altogether if a severe bump was encountered. It can be hypothesized that these phenomena, if they in fact occur, are likely to have more influence on single-vehicle accidents than multiple-vehicle accidents where the accident process is much more complex.

To test this hypothesis, single-vehicle accidents involving combination vehicles as reported by the aforementioned four states have been broken down into collision and non-collision accidents. The first column in Table 9 shows the proportion of single-vehicle combination vehicle accidents that do not involve a collision. Also shown (see the second column) is the proportion of these accidents where the prime event coded in the police report is the vehicle overturning. The states seem to fall into two groups, with Michigan and Pennsylvania forming one pair, Texas and Washington the other. The first pair has a substantially smaller proportion of single-vehicle accidents that are non-collision, and also a smaller proportion of vehicles overturned. The proportion of vehicles overturned in Washington is almost as high as the proportion of all non-collision accidents in Pennsylvania. Additional detail on non-collision accidents is available from the BMCS accident reports. Table 10 shows the proportion of single-vehicle involvements listed as "ran-off-road," "overturn," and "jackknife" as the primary non-collision event.

In general, non-collision accidents are a much higher proportion of all single-vehicle involvements in the BMCS data than in the state files. However, no information is available in either set of files which can attribute a portion of these "loss-of-control" accidents to a vibratory event. This is not to say that vibratory phenomena have not contributed to the single-vehicle accident record, only that the record itself does not contain information which permits us to test the hypothesis.

On the other hand, both the Texas and Washington files code "foot slipped off clutch or brake" under "contributing circumstances." This factor is indicated in less than 0.1 percent of the accidents involving combination vehicles. Existing data indicate that problems in this aspect of motor control, whether vibration-induced or not, are not a significant contributing factor to the accident record.

A second way of testing the hypothesis that vibration can lead to a loss-of-control event is to consider those accidents in which holes, ruts, or bumps in the road are coded as a factor. The frequency with which broken pavement is coded in three of the four state files is shown

Table 9. Non-Collision Accidents and Vehicles Overturned as Proportions of All 1978 Single-Vehicle Tractor Involvements.

State	Accident Type	
	Non-Collision	Vehicle Overturned
Michigan	32.2%	14.5%
Pennsylvania	28.9%	13.7%
Texas	44.7%	25.2%
Washington	43.9%	27.1%

Table 10. Non-Collision Accidents as a Proportion of All Single-Vehicle Tractor Involvements.

1978 BMCS

Accident Type	Number	Percent
Ran-off-road	2032	23.2
Overturn	2219	25.3
Jackknife	1395	15.9
Other	743	8.5
All Non-Collision	6389	72.9

in Table 11. As would be expected, this factor is cited more frequently for single-vehicle involvements than for multiple-vehicle involvements. It should be noted, however, that broken pavement generally does not result in accidents containing a high risk of injury or fatality. Table 12 shows that no fatalities occurred in these three states and that the injury risk is not very high. In addition, the 1978 FARS file shows that ruts, holes, and bumps in the road were reported as a contributing factor in three fatal accidents involving a combination vehicle. (Although three fatal accidents cannot be viewed as insignificant, the fact that ruts, bumps, and holes were coded in the files does not mean that they were instrumental in causing a vehicle vibration; rather, the accident may have resulted from the driver taking action to evade the pavement defect. Further, this finding should be tempered by the fact that roadway maintenance or construction, namely, the action required to eliminate pavement defects, was reported as a contributing factor in 44 fatal accidents involving combination vehicles in that same year.) From the accident data, then, it would appear that existing levels of highway maintenance are sufficient to prevent pavement defects from making a significant contribution to the accident record.

Lastly, the accident record should be examined to see whether long-term exposure to whole-body vibration causes accidents that could be attributed to driver fatigue. Clearly, this examination will be difficult since the effects of fatigue are pervasive, ranging from decreased vigilance to impaired driver reactions and judgments to actually falling asleep. The primary problem is that the reporting police officer generally has no basis for concluding that fatigue is a factor other than the evidence that the driver fell asleep, or was nearly on the verge of doing so. In many states, the accident report does not permit the reporting officer to desigate "fatigue" as a factor, rather he is constrained to indicate that the driver was "asleep" or "ill." Table 13 shows the proportion of combination vehicle accidents in which the police identified the driver as being "fatigued," "asleep," or "ill" in the four states whose files were suitable for conducting this analysis. It is observed that these three driver descriptors are consistently coded more frequently for single-vehicle accidents than for multiple-vehicle accidents in which a combination vehicle is involved. Table 14 shows a

Table 11. Proportion of Involvements Coded with Broken Pavement as a Contributory Factor by Accident Type.

State	Accident Type		All Accidents
	Single-Vehicle	Other	
Michigan	0.6%	0.04%	0.1%
Pennsylvania	2.1%	0.2%	0.8%
Texas	0.5%	0.1%	0.2%
Washington	NA	NA	NA

Table 12. Single-Vehicle Tractor Accidents Involving Broken Pavement by Injury Severity.

State	Most Severe Injury in Accident			TOTAL
	No Injury	Injury	Fatality	
Michigan	91.7%	8.3%	0.0%	100.0%
Pennsylvania	71.4%	28.6%	0.0%	100.0%
Texas	77.8%	22.2%	0.0%	100.0%
Washington	NA	NA	NA	NA

Table 13. Proportion of Involvements Coded as Driver Fatigued, Asleep, or Ill by Accident Type.

State	Accident Type		All Accidents
	Single-Vehicle	Other	
Michigan	1.2%	0.2%	0.4%
Pennsylvania	2.5%	2.3%	2.4%
Texas	3.7%	0.3%	1.1%
Washington	5.0%	0.3%	1.4%

Table 14. Single-Vehicle Tractor Accidents Involving Driver Fatigue or Illness by Injury Severity.

State	Most Severe Injury in Accident			TOTAL
	No Injury	Injury	Fatality	
Michigan	45.8%	50.0%	4.2%	100.0%
Pennsylvania	35.3%	56.9%	7.8%	100.0%
Texas	33.6%	59.9%	6.6%	100.1%
Washington	51.5%	39.4%	9.1%	100.0%

further breakdown of single-vehicle accidents in which driver fatigue or illness is coded. The relative proportions are given for three gross levels of injury severity, namely, no injury, injury, and fatality. It should be noted that fatal accidents are much more common when fatigue or illness is implicated in a single-vehicle accident than is true for all single-vehicle accidents involving combination vehicles, as shown in Table 15.

The accident reports submitted to the BMCS indicate the number of hours the driver had been on duty at the time of the accident. Table 16 shows the distribution of hours on duty for all tractor involvements reported to the BMCS by authorized carriers in 1978. About 60 percent of the involvements listed in Table 16 occurred when the driver had been on duty four hours or less. The number of drivers that were reported to have been sick or have dozed at the wheel is also shown in Table 16 for each reported hour on duty. The percentage of drivers recorded as dozing or sick has been calculated for each hour on duty. This percentage steadily increases from 0.9 percent during the first hour on duty to 8.3 percent during the eleventh and twelfth hour.

These tables provide a fairly comprehensive picture of the extent to which combination vehicle accidents involve extreme fatigue or illness on the part of the driver. Clearly, these factors may be involved more than indicated here, in a manner that is too subtle to detect by means of existing data collection programs. Further, to interpret Table 16 in a meaningful way, one needs information on the vehicle mileage that is accumulated as a function of the hours that drivers have been on duty. Since such data are not available, we are limited in the conclusions that we can draw relative to fatigue as a factor in causing accidents. Whether fatigue is influenced by the presence of vibration, either positively or negatively, is clearly not deducible from the accident record.

2.4.4 Concluding Statements.

1. Given accident data files in their existing form and the current state of accident causation research, it is not possible to establish any significant link between ride vibrations and accident

Table 15. Fatal Involvements as a Proportion of All 1978 Police-Reported Tractor Involvements.

State	Accident Type		All Accidents
	Single-Vehicle	Other	
Michigan	0.8%	1.6%	1.4%
Pennsylvania	1.6%	3.5%	2.9%
Texas	1.4%	2.8%	2.5%
Washington	0.9%	2.2%	1.9%

Table 16. Distribution of Tractor Involvements by Hours on Duty and Proportion of Drivers Dozing or Ill.

1978 BMCS -- Authorized Carriers

Hours on Duty	Number	Percent	Cum. Percent	Dozed or Ill	Percent for Each Hour
1	4320	17.7	19.0	38	0.9
2	3217	13.2	33.2	41	1.3
3	3178	13.0	47.1	44	1.4
4	2999	12.3	60.3	53	1.8
5	2520	10.3	71.4	49	1.9
6	2123	8.7	80.8	46	2.2
7	1705	7.0	88.3	43	2.5
8	1347	5.5	94.2	26	1.9
9	899	3.7	98.2	22	2.4
10	310	1.3	99.5	11	3.5
11-12	109	0.4	100.0	9	8.3
Not App.	1465	6.0	--	22	1.5
Unknown	255	1.0	--	9	3.5
Total	24447	100.1	--	413	1.7

involvement. In those cases where the accident data files provided sufficient detail to examine hypothesized mechanisms, the possible occurrences were infrequent. For other mechanisms, the existing data were inadequate.

2. With regard to short-term effects of ride vibration—degraded vision in vibrating mirrors, reduced proficiency in control modulation, and loss of control due to severe bumps—the available data do not provide significant evidence to support the hypothesized mechanisms relating these short-term vibratory effects to accident involvement.

3. Thus, the most likely connection between truck ride quality and accident involvement is the synergism between multi-hour exposure to vibration and all of the other negative aspects associated with driving a heavy goods vehicle. (For lack of a more objective definition of the manner in which drivers respond and react to a host of negative elements, both internal and external, we are forced to refer to this ill-defined state as "fatigue.")

The available accident data indicate that extreme fatigue (falling asleep) is a contributing factor to a significant fraction (1-2 percent) of all combination vehicle accidents and 2-4 percent of all fatal combination vehicle accidents. It is reasonable to conjecture that less extreme fatigue has a more pervasive influence on aspects of the driving task, such as vigilance. However, the available data provide no means of identifying the contribution of ride vibrations to fatigue. Thus, the most likely hypothesis relating ride vibrations and accident involvement is the interaction of vibration with all of the other stresses associated with driving a heavy truck. The current state of knowledge is not adequate to evaluate this hypothesis.

4. In general, the existing literature and the above interpretation of the accident data do not provide evidence that the hypothesized mechanisms relating truck ride vibrations to accident involvement are important or significant. This finding does not necessarily imply that ride vibrations do not contribute significantly to highway safety. However, if ride vibration does contribute significantly to highway safety, it means that the mechanisms operating may be more complex than those hypothesized or that more detailed data and sophisticated analysis techniques are required.

3.0 THE RELATIONSHIP BETWEEN TRUCK RIDE VIBRATION AND HIGHWAY SAFETY: FINDINGS OF A CONFERENCE

3.1 Conference Goals and Design

From the inception of this project it was recognized that hard evidence was unlikely to exist by which to draw scientific conclusions on the contributions of truck ride vibrations to the accident record. The convening of a conference of knowledgeable parties was adopted, a priori, as an appropriate means to address the issue. The conference approach ensured that the information base from which the significance of the issue was to be evaluated was not limited only to published knowledge, but included unpublished knowledge, as well as the practical experience accrued by those with direct involvement in the subject. The conference format also provided means to develop judgments, in the absence of hard evidence, representing a consensus drawn from a broad range of interests.

3.1.1 Conference Goals. The primary goals of the conference were the development of substantive information as to the significance of truck vibration, firstly to safety and secondly to driver's health. Inasmuch as the results would necessarily rely on judgments, experience, and even intuition, more specific goals were established as follows:

1) To achieve as much clarity and consensus as is feasible concerning the causal linkages between ride vibration and the accident record by (a) critique of the accuracy and adequacy of the State-of-Knowledge Review and (b) the development of "truth" statements from the conference participants.

2) To obtain measures of the perceived importance of truck vibration to safety and health from the collective group.

3) To develop recommendations for courses of action seen as appropriate by the group.

3.1.2 Selection of Participants. The goals of the conference dictated the assembly of a spectrum of participants who possess different perspectives on the issues involved. Accordingly, the question of who should participate resolved to the question of which constituencies should be represented. For the purposes of this conference, it was concluded that the following groups should be represented:

a) the truck driver,

b) the trucking industry,

c) the manufacturer of trucks and truck components, and

d) the highway community.

Within each category, the specific choice of individuals must appropriately cover the spectrum from those with direct experience in the industry, to those with a scientific background in the area. As an example, the truck driver's interest was seen as needing representation from the level of an experienced truck driver, to researchers and scientists concerned with the effects of vibration on man as would affect driving performance. In the last category, it should be noted that federal government staff representing the sponsors of the conference also attended, both as participants and observers.

With the constituencies thus defined, 30 prospective conferees agreed to participate in the conference, of which 26 attended. (A list of conference attendees will be found in Appendix A.)

3.1.3 Conference Design. In proceeding to develop a "Conference Plan" (as defined and required by Task A of the work statement), HSRI staff quickly concluded that the objective of developing a consensus was not likely to be realized unless the structure and format of the meeting were specifically designed so as to facilitate conferral and generate a dynamism in the discussions and interactions occurring between the various conferees. To this end, the assistance of Dr. R. Lippett and associates was obtained to help in the design and conduct of the conference.

Aside from the general considerations required for procedural matters, the conference was designed around a three-step process, characterized as follows:

1) Education - Prior to the conference, a state of the knowledge document addressing the relationship of truck ride vibration to highway safety was prepared and sent to each participant. The document attempted to provide background information and a basic structure to the links between vibration and safety, hypothesizing what links might exist in order to provoke thought and discussion. Additionally, at the outset of the conference the participants were exposed to the various viewpoints on the issue by hearing informal discussion from principals representing the historical perspective, as well as that of the interest groups involved.

2) Assessment - With this background in all the various aspects of the issue, the participants were given brief presentations on the published technical knowledge relevant to each link in the connection between vibration and safety. Then, in a setting of groups comprised of persons from each of the special interest areas, the participants were asked to assess what was known and not known about that aspect of the issue.

3) Products - In the latter portion of the conference, the participants were challenged to apply their working knowledge, judgment, and opinion or intuition, based on their confrontation with the issue, to provide products desired from the conference. These products include an appraisal of what is known and not known relative to the issue, including their consensus on these "truths." The second product was their judgment as to the importance of vibration among the many factors which bear on the safety

> of the highway/vehicle/driver system. And finally, the participants were asked to propose courses of action appropriate to each constituency as suggested from their consideration of the issues.

To facilitate the above-defined process, a conference spanning three days (viz., a Sunday-evening session, a full day on Monday, and a three-quarter day on Tuesday) was held. (An outline of the conference schedule will be found in Appendix A.) Given the desire for maximizing the opportunities for dialogue, the conferees were divided into small working groups in order to facilitate group interaction and discussion. At the beginning of the conference, the groups were comprised of a heterogeneous mixture of the constituencies that were present. This arrangement served a dual purpose. First, it provided for a variety of points of view and backgrounds being brought to bear as attendees sought to generate acceptable generalizations (truth statements) from the knowledge and "facts" that were presented. Second, it provided opportunities for participants to have their horizons broadened, since the discussion at each table reflected a wide variation in professional responsibilities and technical disciplines.

On Tuesday, however, the working groups were homogeneous in their make up (see Appendix A for a listing of the heterogeneous and homogeneous groupings used in the course of the conference). This latter seating arrangement permitted participants who had similar backgrounds and vested interests to filter the statements generated by the various heterogeneous groups (on the previous day) through their own special concerns. In this manner, any concern that a particular constituency did not get an adequate hearing was greatly mitigated. The recommendations for courses of action were generated by homogeneous groups in the expectation that each group would best identify the individual constituencies to be charged with that responsibility. The development of consensus proceeded in three stages—first, within heterogenous groups of conferees, then within homogeneous groupings, and finally, within the conference as a whole, wherein each group interacted (in a give and take way) with other groups so as to arrive at truth statements, conclusions, and recommendations broadly acceptable to all present.

Several subordinate features of the conference involved activities that assisted each attendee to appreciate that one's point of view is highly dependent on the background that he (or she) brings to a meeting of this kind. For example, as indicated above, each conferee was made familiar with the thinking, experiences, and advocacy actions which led to the establishment of the truck ride/safety project within the Federal Highway Administration by having an informal interview session (on Sunday evening) with the then FHWA Associate Administrator for Safety, who had a key involvement in the establishment of the project. In addition, conferees were exposed, via informal interviews on Monday, to the views held by their peers on the overall nature of the truck safety problem and on the extent to which the truck accident record is influenced by factors other than truck ride quality. Exposure to this latter set of views was accomplished by means of an Opinion Survey (see Appendix A) which required that each conferee render a judgement on the relative contribution of various driver/vehicle/roadway factors to the accident record, preliminary to rendering a judgment as to the relative importance of truck vibration as a mechanism leading to traffic accidents. By feeding the results of this survey back to the conferees as soon as the data could be processed, the conferees obtained feedback on how their views compared with those of their peers and also gained insight on the extent to which different constituencies saw the world somewhat differently.

3.2 Conference Products

The products of the conference are compiled here in terms of three types of results—the findings of an Opinion Survey, a set of "truth statements," and a set of recommendations. (The interpretations drawn from these products are contained in Section 4.0.) Each of these products serves to register the individual and collective views of the conferees on the significance and character of the truck ride problem. To the maximum extent possible, the presented material accurately reflects the specific statements and recommendations actually made by conference participants. The authors have exercised an editing role to add to the clarity of the statements where deemed appropriate. In the editing function, the authors have tried to be guided by the context of the discussion and debate which ensued during the progress of the conference itself.

3.2.1 Opinion Survey

Part One - Ranking of Accident Factors

On the first evening, the conferees were given an Opinion Survey form (see Appendix A) to fill out prior to convening the opening session. As indicated earlier, the purpose of the Survey was to provide some scale of comparable issues against which to measure the significance of the vibration/safety issue. The Survey required the conferee to rank three sets of factors which were selected as having some potential connection with the accident involvement of heavy trucks. The factors were organized into the following sets:

-Vehicle Factors

-Highway Factors

-Truck Driver Factors

Each set consisted of eight factors, often identified as having a potential relevance to highway safety. The participants were instructed to rank the eight factors to reflect their view of the relative importance of each as contributors to truck accidents. The instruction sheet acknowledged that the participants may have had little information or experience from which to draw their ranking choices.* The specific ranking

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*It should be noted that some of the participants objected to collection and use of the data in both Parts One and Two of this Opinion Survey on the basis that they had no expertise or other information from which to make judgments. Others were concerned that data existed by which to establish factual answers to the questions asked on the survey, in which case they were not matters of opinion at all. In general, the necessary information does not exist, hence opinions are all that are available.

The authors appreciated those concerns, however, under the circumstances it was felt that this was the most appropriate way to was not of direct importance. Rather, it was acquired to serve as a relative scale, prior to any discussions of vibration, against which to rank the significance of vibration. These initial lists did not include any ride-vibration-related factors. In a subsequent ranking activity on the second day of the conference, the conferees received their first ranking forms back and were asked to place ride-related factors relative to the other factors which had been previously ranked.

The results of this exercise are presented in Figures 29, 30, and 31. Note that each figure shows the average rank order of each factor as established by the conferees within each of the three above-mentioned sets. Although individual rankings could range from one to eight, the averaged results typically range from 2 to approximately 6.5.

In the Vehicle Factors set (Fig. 29), the averaged rankings reported by the overall group (on the right side of the figure) range from 2.8 to 6.5, with "Poor Maintenance" and "Poor Truck Conspicuity" defining the most and least important factors, respectively. The other six Vehicle Factors have rank values which cover a narrow range, but which are rather distinctly separated from the first- and last-ranked items. The narrow grouping is generally indicative of disagreement among the conferees as to the order of priority for these factors. (A random ranking would place each factor at a value of 4.5.) At the left side of the figure, the rankings of a factor labeled "Rough Ride Vibrations" are shown as determined by each of the four groups into which the conferees were divided on Tuesday, namely,

-Driver Group (including those involved in research on human tolerance to vibration, and others concerned with the health and safety of truck drivers)

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measure judgments. In Part One, the eight-item scales were obtained only for the purpose of determining whether ride-related factors were considered to be of more-, equal-, or less-importance than other common safety issues; and the authors have tried to portray the results only in that light. Part Two was an attempt to measure judgments as to where vibration-related factors have their most impact on highway transportation, again using the results with a sensitivity to their meaning. The authors apologize to any of the participants who feel that the attempts to measure judgments were inappropriate to the conference.

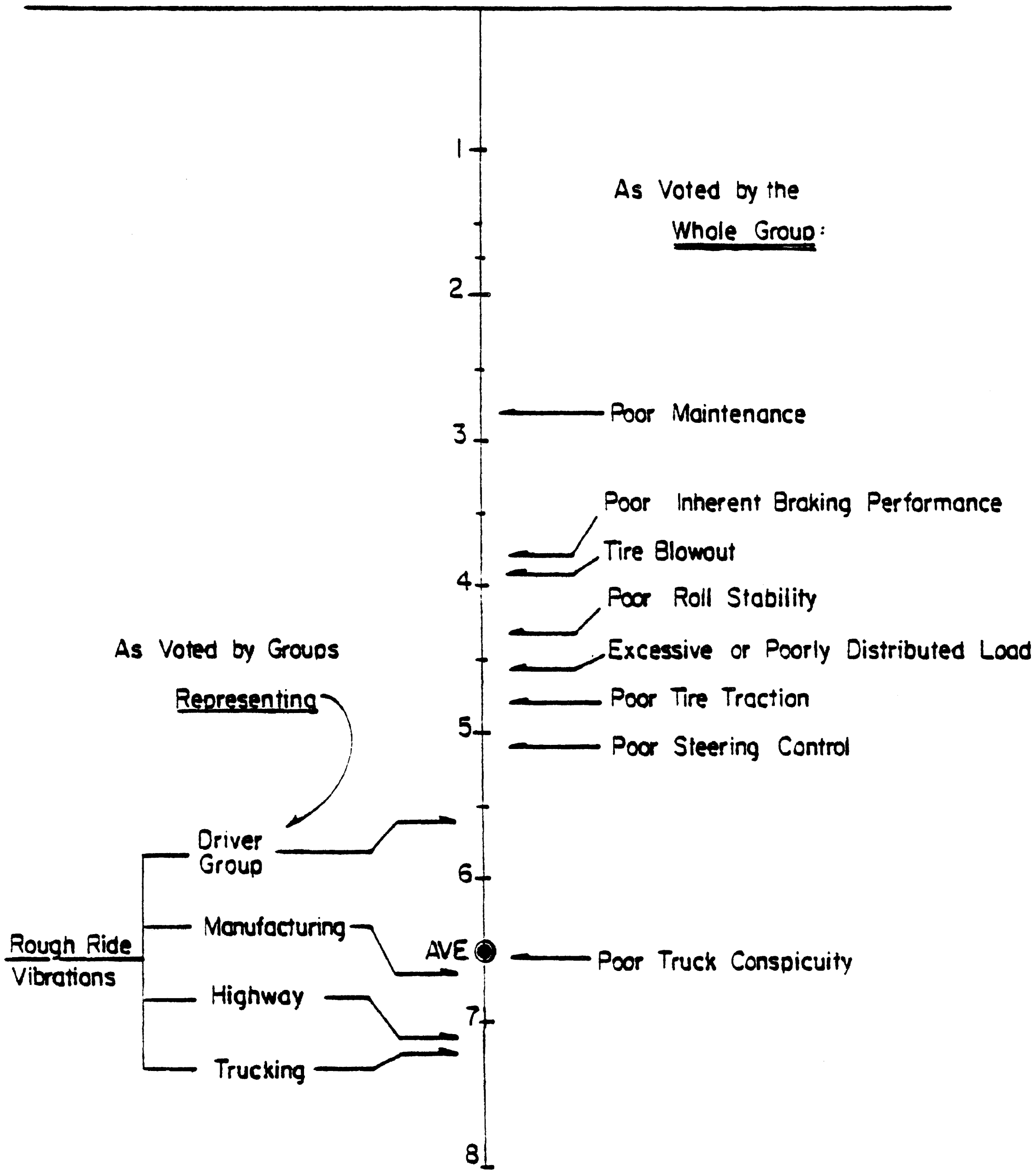


Figure 29. Rank order of vehicle factors, in terms of their relative importance as contributors to truck accidents.

- -Manufacturing (including those employed by motor vehicle, trailer, and vehicle component manufacturing organizations or their trade associations)
- -Highway (including those involved in highway engineering and research)
- -Trucking (including those involved in motor freight operations, motor carrier safety regulation, and trucking trade associations)

The average ranking obtained for "Rough Ride Vibrations" as a contributing factor to accidents is 6.5, a ranking approximately equal to that given to "Poor Truck Conspicuity," which falls at the bottom of the initial ranking list. Given that the standard deviation of the rankings for the rough ride factor is 1.6, the specific differences obtained in the rankings given by the four interest groups is not of great significance, but is indicative of general agreement that rough ride vibrations are of low priority among <u>truck</u> factors contributing to accidents.

Figure 30 shows the rank order given to Highway Factors as potential contributors to truck accidents. On the right side are the factors which were ranked before the start of the conference, showing "Slippery Pavement" as the distinctly first-ranked item, followed by "Poor Interchange Design" and "Inadequate Bank on Curves." The very tight grouping of the five remaining factors in a virtual last place is indicative of little agreement among the participants as to their order of importance. At the left of the figure are shown the rankings given by the four respective interest groups to the highway factor "Distributed and Localized Roughness." In this instance, the pavement roughness factor has been given an average rank of 5.1—a value that places it in the vicinity of the five closely grouped factors as ranked initially by all of the conferees. The standard deviation of the ranking given to the highway roughness factor is 2.1, again indicating that the spread in rankings yielded by the four interest groups is of marginal significance.

In Figure 31, the ranking of Truck Driver Factors is presented. The results show that the conferees viewed "Aggressive Driving Tactics"

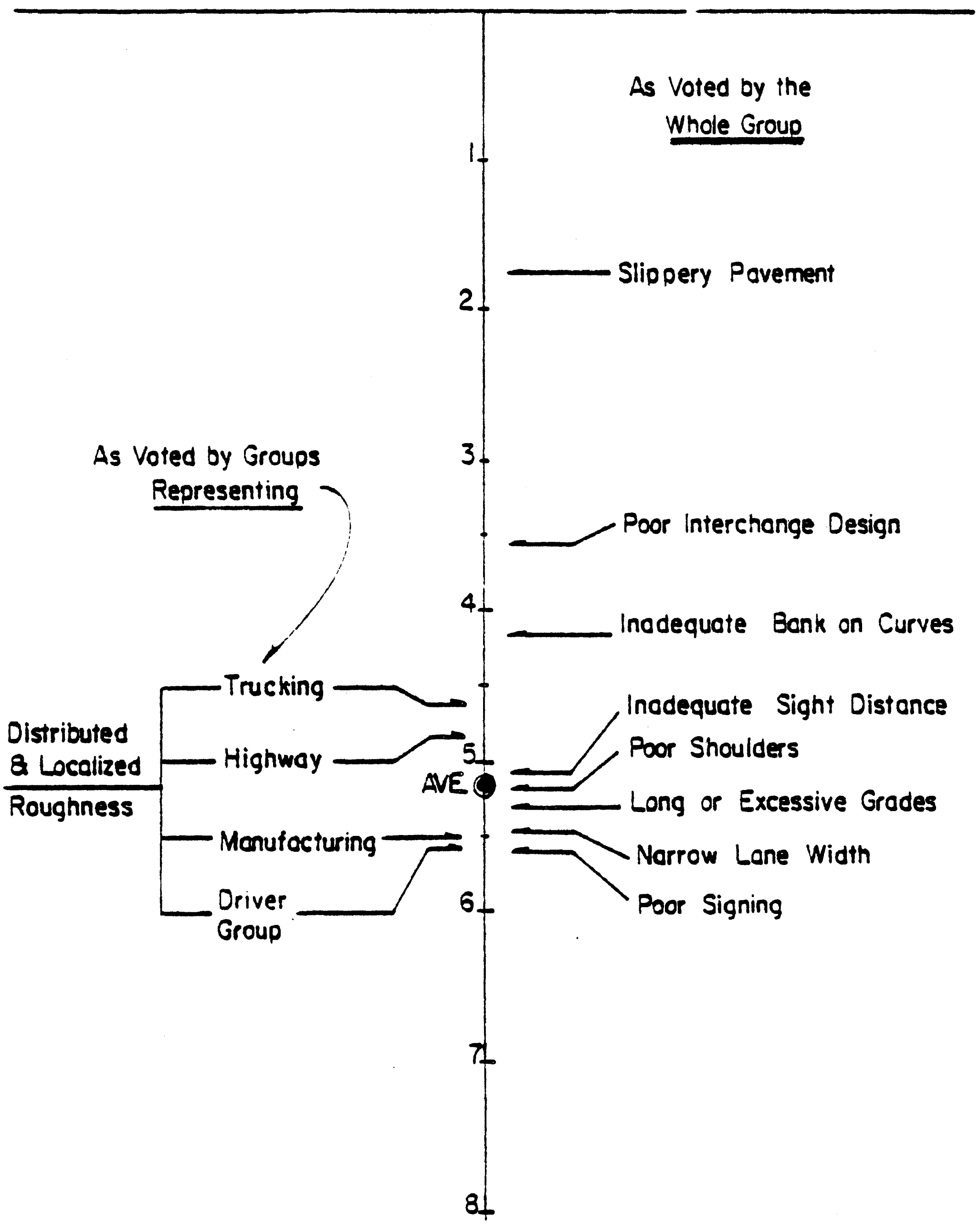


Figure 30. Rank order of highway factors, in terms of their relative importance as contributors to truck accidents.

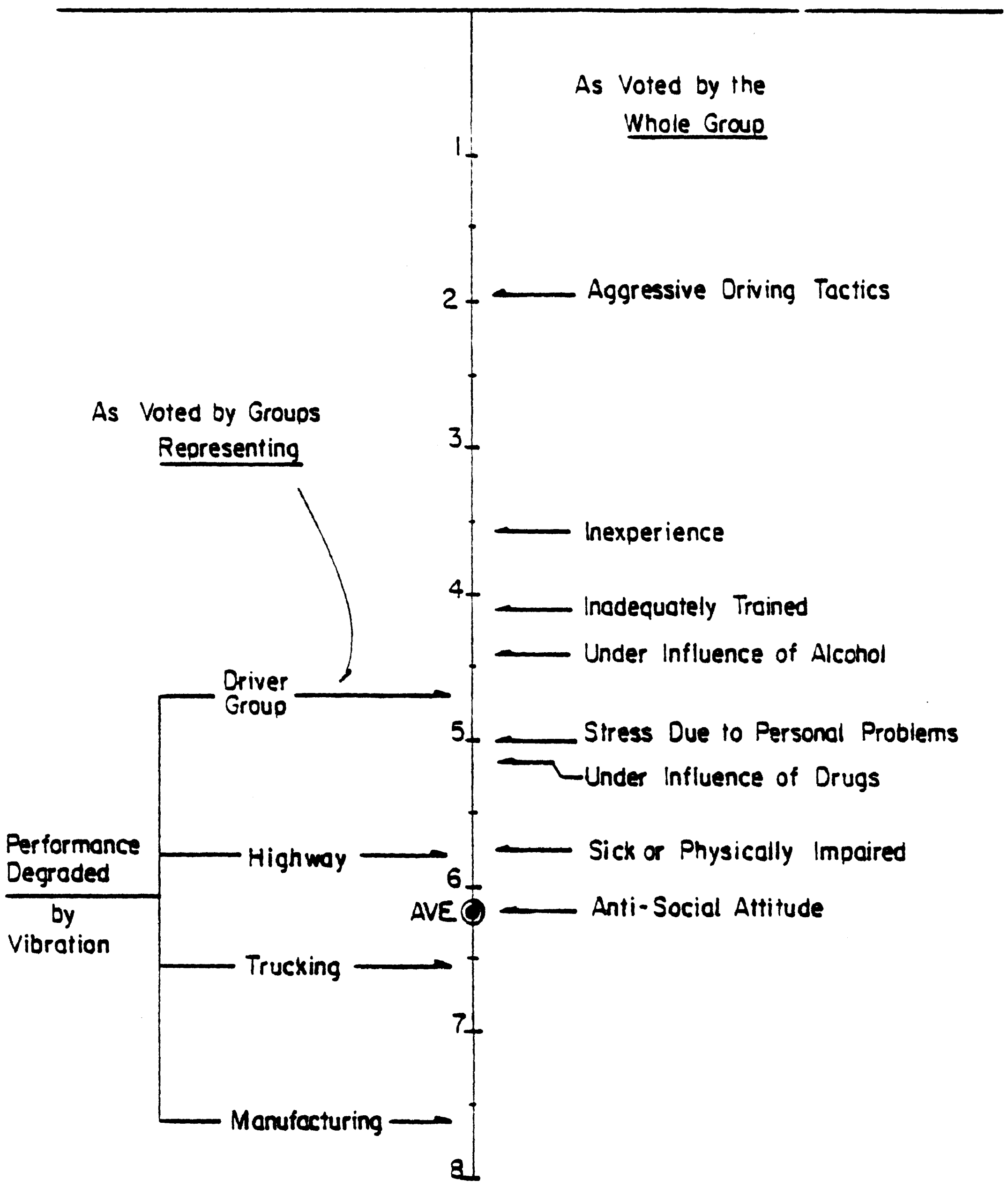


Figure 31. Rank order of driver factors, in terms of their relative importance as contributors to truck accidents.

as a decidedly important factor, with a fairly broad distinction of rankings obtained for the other seven factors, ranging from 3.5 to 6.2. On the left side are shown the rankings given by each interest group to the factor labeled "Performance Degraded by Vibration." Although a larger spread in the rankings given to this ride-related factor by the four interest groups is evident, the average ranking again appears at the bottom of the scale as developed in the initial ranking exercise. It should be noted that the standard deviation of the rankings obtained for the vibration factor is 1.9.

The ranking of ride-related factors was determined as a function of the respective interest groups on the supposition that the differing groups possessed differing levels of information or experience in each of the subject areas, viz., vehicle, highway, and driver factors. For example, it might be assumed that the vehicle manufacturers and trucking organizations would have a stronger basis upon which to rate the importance of ride vibrations among vehicle factors because of their direct involvement in vehicle design and usage. Following this line of reasoning, we observe that:

1) Individuals in the manufacturing and trucking groups placed the truck factor, "Rough Ride Vibrations," lower in rank than the average ranking produced by the entire group of conferees.

2) The highway group ranked the highway factor, "Distributed and Localized Roughness," slightly, but insignificantly, higher than the average ranking.

3) The driver-oriented group placed the driver factor, "Performance Degraded by Vibration," significantly above the average ranking established by the conferees at large. Given the number of individuals in the driver-oriented group, as well as the overall group, we can be 80 percent confident that the mean value of the driver-oriented group's ranking would be above the overall mean should a larger data sample be taken (assuming normal distribution).

Whereas this observation may be statistically satisfying, the net outcome appears to be that all of the interest groups have placed this vibration-related driver factor near the bottom of the overall rankings, with the driver-oriented group giving a somewhat higher importance to the driver factor.

Part Two - Numerical Estimates

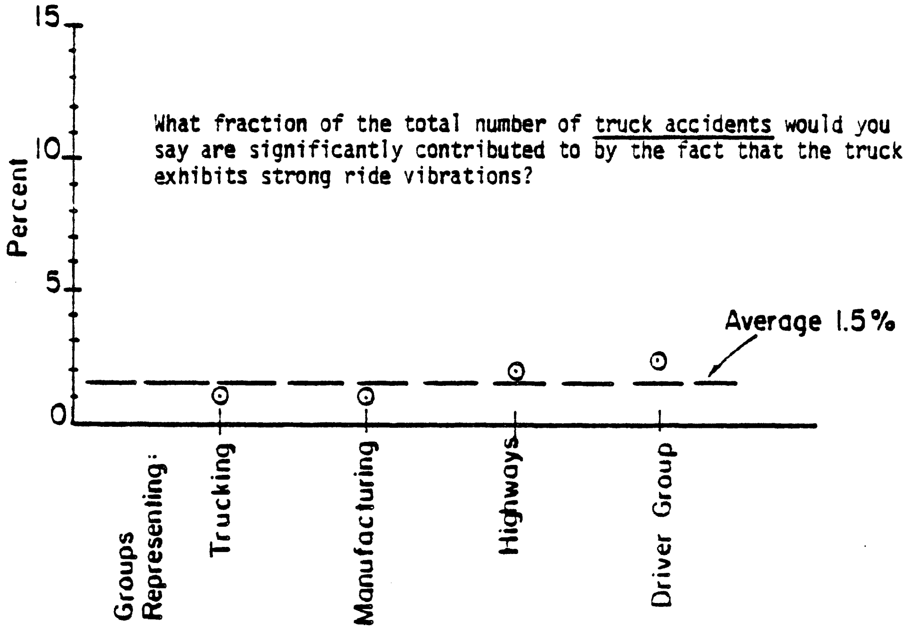
Following this establishment of the relative importance of vibration as a contributor to the accident record, a second part of the Opinion Survey was administered to obtain some absolute readings. Specifically, questions were posed asking for a numerical estimate of the involvement of vibration-related factors in the causation of:

1) accidents,
2) driver health problems,
3) freight damage, and
4) component wear and degradation.

The first two factors were of primary interest, the last two being included simply to provide a supplementary measure for evaluating the results.

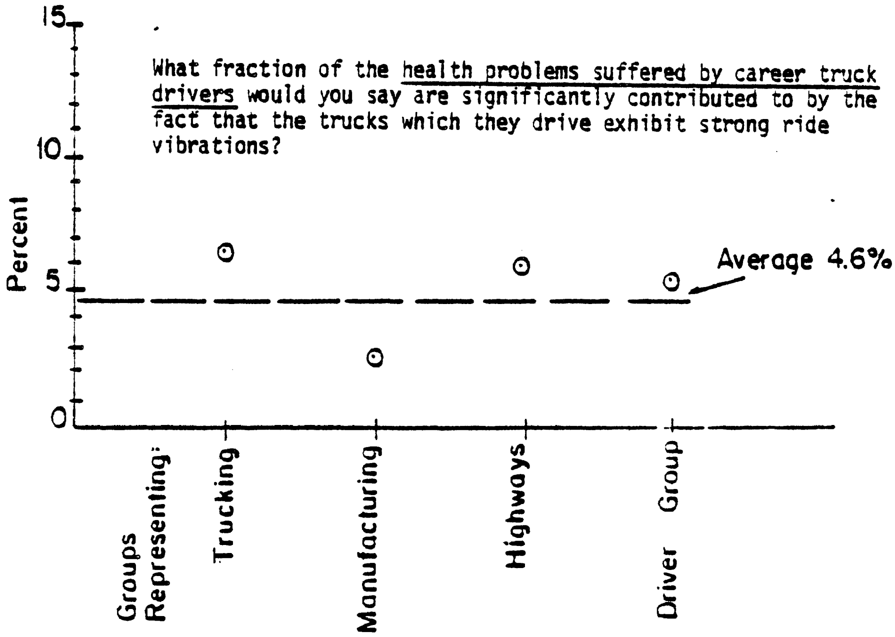
At the time Part Two was administered, the conferees had heard and discussed the evidence linking vibration to safety, with secondary considerations of health. The Survey now asked for their considered judgment based on the weighing of that information.

In response to each question, the conferees were asked to check one of the seven boxes (as shown below) to indicate his estimate (or guess) of the likely involvement of a vibration-related factor. Shown in Figures 32 through 35 are the results as complied for the four interest groups, as well as for the conferees at large. Figure 32 illustrates the percentage of truck accidents estimated by the conferees as being significantly contributed to by the fact that the involved trucks exhibited strong ride vibrations. The overall, and the individual interest group, estimates were in the vicinity of 1 to 2 percent.



What fraction of the total number of truck accidents would you say are significantly contributed to by the fact that the truck exhibits strong ride vibrations?

Figure 32. Opinion Survey results for truck accident relationship to ride vibration.



What fraction of the health problems suffered by career truck drivers would you say are significantly contributed to by the fact that the trucks which they drive exhibit strong ride vibrations?

Figure 33. Opinion Survey results for driver health relationship to ride vibration.

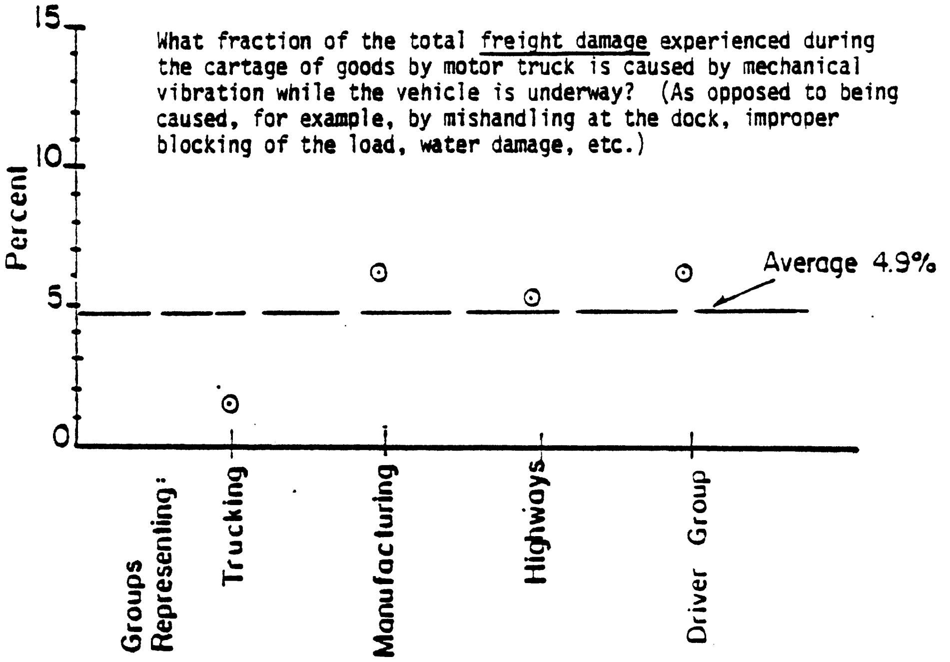

What fraction of the total freight damage experienced during the cartage of goods by motor truck is caused by mechanical vibration while the vehicle is underway? (As opposed to being caused, for example, by mishandling at the dock, improper blocking of the load, water damage, etc.)

Figure 34. Opinion Survey results for freight damage relationship to truck vibration.

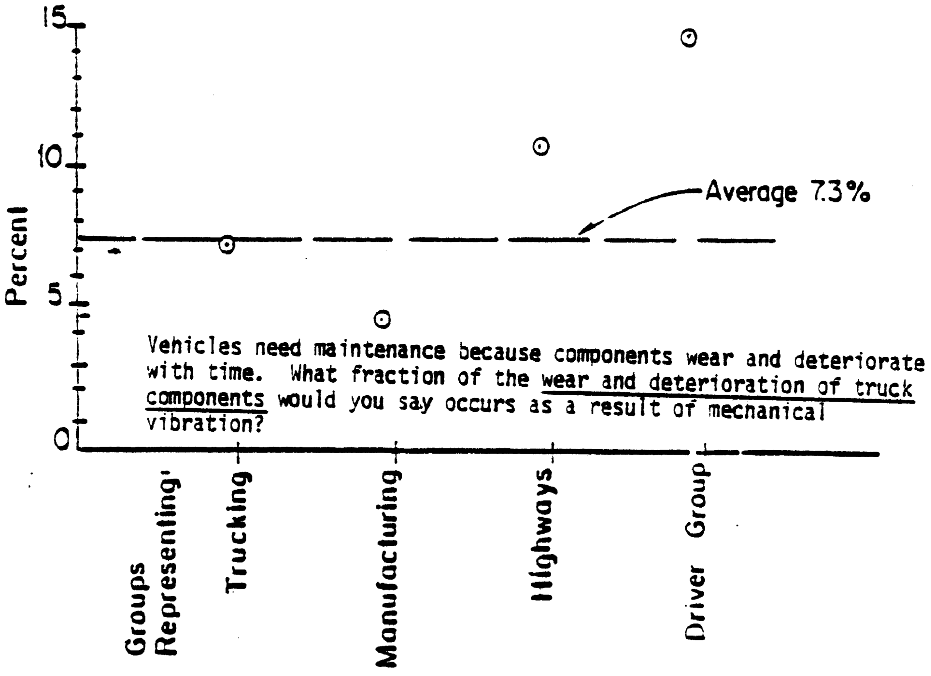

Vehicles need maintenance because components wear and deteriorate with time. What fraction of the wear and deterioration of truck components would you say occurs as a result of mechanical vibration?

Figure 35. Opinion Survey results for wear and deterioration relationship to truck vibration.

☐ less than 1%   ☐ 1 to 2%   ☐ 2 to 5%   ☐ 5 to 10%

☐ 10 to 20%   ☐ 20 to 50%   ☐ Over 50%

In estimating the likely contribution of ride vibration to the health problems suffered by career truck drivers, the conferees produced the results shown in Figure 33. More scatter exists in the values registered, with the average percentage fraction being 4.6 percent.

In Figure 34, the estimates of the contribution of ride vibration to the incidence of freight damage during the cartage of goods is shown. One conferee pointed out, during verbal discussion of these results, that only trucking organizations would be likely to have any direct experience with the freight damage problem. Accordingly, he suggested that it is significant that the "Trucking" group entered an estimate which was markedly lower than those entered by all other groups. (It should also be stated that 50 percent of the conferees elected not to enter an estimate for "freight damage.")

In Figure 35, we see that the conferees at large estimated that 7.3 percent of the wear and deterioration of truck components can be attributed to the mechanical vibration induced by road roughness. Again, it is noted that the driver-oriented group, which probably possesses the minimum basis for making such an estimate, placed this factor at 15 percent, while the manufacturing group (presumably having the greatest basis for making an estimate of this influence) produced an estimate of approximately 4 percent.

3.2.2 Compiled Truth Statements. A major output of the conference consists of "truth statements" reflecting the participants' views of the most significant facts or judgments which describe the current state of affairs with regard to truck ride and traffic safety. Certain of these statements address the focal issue (i.e., ride versus safety) of the conference. Other statements speak to the state of the sciences and the technologies which, limited though they may be, form the basis for determining the factual relationship between ride and safety.

Presented below are the final versions of the "truth statements" which were produced by the conferees. The statements were developed in the following manner:

a) On the second day of the conference, each of the heterogeneous groups compiled statements of truth subsequent to hearing brief presentations on the state of knowledge in each subject area.

b) The conference staff edited and combined these statements into a set which was reproduced and distributed for consideration by the homogeneous groupings on the third day.

c) Each homogeneous group went through this combined set of statements and selected those which, with perhaps some modification, represented the points which they most wanted to present to the conferees at large in seeking a consensus endorsement. Each group presented one statement for consideration and voting by the conferees at large. As each statement was presented, suggestions were entertained from other participants for possible modification of the statement. After all suggested modifications had been considered by the group which originally offered the statement, votes were taken to determine (1) the number of participants who agreed and disagreed with the (as-modified) statement and (2) the number of conferees who felt that the statement was important to the issue.

d) Step (c), above, was repeated in the time available until each interest group had the opportunity of presenting at least three statements for consideration by the conferees at large. In a few cases, a specific interest group opted to produce a completely new truth statement and offer it for voting by the conferees at large.

Preceding each truth statement (listed by the group of origin) is the vote tally which registeres the degree of AGREEMENT or DISAGREEMENT and the degree of IMPORTANCE assigned by the conferees to each statement. It should be noted that at the beginning of this session, 25 participants remained in attendance. As the session proceeded, however, certain persons were being pressed by their travel schedules such that only 21 persons remained at the time of the last vote-taking.

Truth Statements Submitted by the Driver-Oriented Group

1) (Agreement: 22 yes, 0 no; Important: 15 yes, 1 no)

ISO (International Organization for Standardization) Standard Number 2631 is the most widely recognized guide for evaluating human response to vibration, but the application of this standard to the truck ride process may require that the boundaries in the standard be adjusted in the light of real data for the truck driving environment.

2) (Agreement: 23 yes, 0 no; Important: 8 yes, 0 no)

If morbidity is associated with long-term vibration exposure or if chronic diseases are present in the truck driver through other causes, the afflicted state of the driver may reduce driving effectiveness as a result of discomfort, stress, fatigue, and distraction.

3) (Agreement: 14 yes, 3 no; Important: 11 yes, 0 no)

Vibration may increase fatigue, and as a result of diminished vigilance and alertness, cause delayed or inappropriate responses to emergency situations; although it must be noted that prior to fatigue, vibration may increase vigilance and alertness.

4) (Agreement: 18 yes, 0 no; Important: 8 yes, 5 no)

Large amplitude momentary vibrations may jar the driver, who is not adequately restrained by a seat belt, from his seat and therefore from a position of control.

5) (Agreement: 17 yes, 4 no; Important: 5 yes, 1 no)

Severe vibration may decrease the driver's ability to manipulate or modulate the steering, braking, and throttle controls in an emergency maneuver.

6) (Agreement: 5 yes, 14 no; Important: 2 yes, 14 no)

Loss of visual acuity incident to mirror vibrations would increase the time required to assimilate rear vision information (a distraction from forward vision tasks) with the possibility for increasing errors in passing and merging maneuvers.

Truth Statements Submitted by the Vehicle Manufacturing Group

1) (Agreement: 18 yes, 1 no; Important: 14 yes, 0 no)

The state of the art in truck design exists to make line-haul trucks "comfortable" on a road surface having a PSI rating of 3.0 or better. (Ed. Note: The designation "PSI" stands for a rating of pavement roughness level called "Present Serviceability Index." An index number of 3.0 pertains to road surfaces which are in fair condition, on the verge of needing resurfacing.)

2) (Agreement: 25 yes, 0 no; Important: 20 yes, 0 no)

There is currently no bank of data available documenting the typical ride vibrations of trucks for real periods of exposure and for yearly driving patterns.

3) (Agreement: 23 yes, 0 no; Important: 19 yes, 0 no)

Any investigations into the relationship between truck ride vibrations and accident involvement must consider interactions between vibration and the other factors contributing to fatigue.

Truth Statements Submitted by the Trucking Group

1) (Agreement: 25 yes, 0 no; Important: 25 yes, 0 no)

Current accident data are not sufficient to establish any significant link between ride vibrations and accident involvement.

2) (Agreement: 23 yes, 0 no; Important: 20 yes, 0 no)

There is insufficient evidence that vibration-induced fatigue is a significant factor in truck accidents.

Truth Statements Submitted by the Highway Group

1) (Agreement: 25 yes, 0 no; Important: 19 yes, 0 no)

We are able, with current methods, to reasonably characterize pavement roughness as experienced by trucks except for two special pavement features, namely:

a) Periodic roughness such as excites truck resonances

b) Local, severe bumps and pot-holes

2) (Agreement: 25 yes, 0 no; Important: 23 yes, 0 no)

With data showing a significant sensitivity of truck vibrations to road roughness, future deterioration of pavements, if uncorrected, is expected to increase the vibration exposure of truck drivers.

3) (Agreement: 8 yes, 0 no; Important: 8 yes, 1 no)

Limited data, currently available, show that a truck driver spends a significant portion of his time driving with vibration levels that exceed the unadjusted ISO four-hour criterion. (Ed. Note: The ISO criterion in question is presented in Figures 27 and 28.)

Although the exercise that produced the above statements served to establish the degree to which the conferees agreed on most points which had been raised during the conference, time was not available to present and vote upon all of the truth statements which had been generated. Listed below are three statements which were included in the set of statements considered by the homogeneous groups and which were recorded on their worksheets as meriting rather broad endorsement:

1) The shape of the ISO weighting curves (i.e., plotting RMS acceleration level versus frequency) is a reasonable way of assessing the relative importance of various parts of the vibration spectrum.
2) There are no applicable data for evaluating the response of humans to short transient excitations such as experienced by the drivers of trucks encountering potholes and the like.
3) There is no standard practice for measuring the ride vibrations applied to truck drivers.

Other statements were considered by the homogeneous groups, but were either discarded as having low importance or were seen as lacking a sufficient consensus within the homogeneous group and thus were not submitted for the voting process.

A third set of truth statements which deserves mention includes those statements which were produced by the heterogeneous groupings after listening to the state of knowledge presentations made on the second day of the conference. As already noted, the conference staff drew from these statements in compiling lists of statements for consideration by the homogeneous groups on the third day. Some of these "statements," however, received a strong but not unanimous level of support from their source group, such that they were not included in the compiled set. On observing that some of these "orphaned" statements had been the subject of a considerable degree of discussion, they are seen as being worthy of inclusion here. Accordingly, the following statements should be seen as having been the subjects of substantial amounts of discussion, albeit with some degree of controversy or lack of general agreement:

1) The phenomenon of "fatigue" is not well understood.

2) The truck driver's problem with respect to safety involves vigilance more than motor-sensory skills such as vision and control. Therefore, if vibration is important to truck safety, the effect of vibration on vigilance is the most important mechanism of concern.

3) Truck vibrations tend to increase muscle tension which initially increases alertness and vigilance, but eventually causes fatigue insofar as it constitutes a form of mild exercise.

4) Interspersed road sections having extended lengths of rough pavement followed by quite smooth sections may pose a peculiar safety problem. (Ed. Note: The scenario under consideration in this statement involves a truck driver sustaining the vigilance-enhancing effect of a rather rough roadway, who then comes onto a quite smooth section of roadway. The stimulus which is provided by the muscle action and exercise associated with the harsh vibration exposure will essentially be absent on the smooth roadway. As the driver then relaxes, it may be that he becomes especially prone to accident threats due to inattentiveness and, perhaps, a state of drowsiness.)

5) Contrary to evidence existing in the literature regarding vibration and stress, drivers report significant "stress" and attitude changes due to rough roads and bumps.

6) Life-style factors typifying truck drivers may be more important causes of health problems (of all kinds) than is vibration.

7) It is erroneous to assume that "cab-over" style road tractors exhibit a ride vibration level that is more severe than that exhibited by "conventional" style tractors.

8) The amount of time and funding required to obtain definitive accident data serving to illustrate the relationship between truck ride vibrations and safety is prohibitive.

3.2.3 Conference Recommendations. In addition to considering and voting upon truth statements, each special interest group submitted recommendations to the conferees at large, which were then voted upon. This exercise constituted the final activity of the conference. Since time was limited at this juncture, there was somewhat less discussion of possible modifications to each proposed recommendation statement. Accordingly, the number of votes in agreement with the statements were, in certain cases, relatively low—presumably due, in part, to differences in wording which may have been minor. The results of this exercise are listed below. Note that the recommendations are listed in terms of the interest group which originated the recommendation. Vote tallies are also shown.

Recommendations Made by the Driver-Oriented Group

1) Initiate research on driver performance and stress effects of the truck driving environment in the following areas: (Ed. Note: Each of the lettered sub-recommendations was voted upon separately as cited.)

a) (Agreement: 18 yes, 0 no)

Potential increase in fatigue, tendency toward drowsiness, etc., due to various factors specific to the truck driving occupation (e.g., vibration, noise, monotony, schedule demands, etc.).

b) (Agreement: 21 yes, 0 no)

Effects of transients on immediate driving performance.

c) (Agreement: 15 yes, 0 no)

Possible long-term health effects.

d) (Agreement: 18 yes, 0 no)

Possible effects of fatigue, monotony, desynchronization (i.e., frequent shifting of normal day/night sleep periods), on truck driving habits.

e) (Agreement: 5 yes, 0 no)

Detection of distant objects under conditions of severe vibration.

2) (Agreement: 13 yes, 0 no)

ISO (International Organization for Standardization) and ANSI (American National Standards Institute) writing groups should be encouraged to work on amendments to ISO 2631 and/or ANSI S3.18-1979 for the application of these documents to the evaluation of truck driver vibration environments. Vibration exposure doses of truck drivers should be collected according to the cited standards for comparison with human response data. High-amplitude, short-duration, single-acceleration transients should receive further consideration in the evaluation procedure.

3) (Agreement: 10 yes, 0 no)

Available quality truck vibration data should be analyzed with respect to improvement of correlations between vibration exposure and subjective ride measures and/or available (e.g., ISO) guidelines. Such truck vibration data should continue to be collected.

4) (Agreement: 17 yes, 0 no)

An experimental program utilizing a driving simulator should be initiated to study connections between truck ride vibrations, driver performance, fatigue, and safety factors.

Recommendations Made by the Manufacturing Group

1) (Agreement: 17 yes, 0 no)

Typical ride vibration data should be gathered which is characteristic of real periods of exposure and yearly patterns as experienced by truck drivers.

2) (Agreement: 22 yes, 0 no)

Research should be conducted to determine the interaction between truck ride vibrations and the other confounding factors that may influence driver performance.

3) (Agreement: 14 yes, 0 no)

The Federal Highway Administration should, through research and development, improve the technology needed to increase highway life expectancy and smoothness and to reduce those vibrations which are input at the frequencies falling in the normal driving range.

Recommendations Made by the Trucking Group

Pending the development of a convincing body of data showing the existence or absence of a positive link between vibration and highway safety, it is recommended that:

a) (Agreement: 17 yes, 0 no)

Research on truck ride quality be encouraged within the private sector (Society of Automotive Engineers, manufacturers, etc.).

b) (Agreement: 17 yes, 0 no)

There be continued research into the long-term health effects of truck driving.

c) (Agreement: 21 yes, 0 no)

Roads be improved and repaired as expeditiously as possible.

d) (Agreement: 21 yes, 0 no)

Simulator techniques should be developed to permit systematic investigation of the various stimuli influencing driver performance.

Recommendations Made by the Highway Group

1) (Agreement: 21 yes, 0 no)

The adverse effects of road roughness on vehicle ride, pavement life, and highway safety should be assessed.

2) (Agreement: 4 yes, 15 no)

Technology should be implemented permitting trucks to be designed so that drivers are isolated from vibrations which affect their ability to control the vehicle.

4.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The relationship between truck ride vibration and safety as explored by (a) an examination of the literature, (b) the conduct of additional truck ride measurements, and (c) the convening of a conference of knowledgeable people involves many diverse aspects. In order to render that extensive and detailed information more easy to assimilate, the findings from this exercise are summarized below in the context of what may be concluded and what likely courses of action would be endorsed by those with a knowledge of the issue.

4.1 Summary and Conclusions

Though the actual data characterizing the long-term vibration exposure of truck drivers are limited in scope, those data which are available give evidence that significant portions of the time spent driving trucks involves exposure to vibrations which, depending on the road surface, approach the ISO/ANSI three-hour Fatigue-Decreased Proficiency Boundary. Whether or not this finding is significant to issues of traffic safety or driver health is a debatable matter. The ISO "FDP" criteria do not constitute a universal "standard" in the sense of an absolute scale and thus require a special effort in their application to the subject of truck ride vibrations. To do so, the technical community sees the need for both more detailed data describing the continuous exposure of drivers over days and weeks and the opportunity to apply the knowledge. Therefore, it must be concluded that the technical community involved in the influence of vibrations on humans does not currently have a basis to provide a direct assessment of the significance of truck ride vibration as it may affect an individual's performance as the driver of a truck, or as it may affect his health.

The conferees who represented the human vibration field of research (i.e., the Driver-Oriented Group) did, however, register their personal "hunches" or suspicions in response to the Opinion Survey question regarding the relative importance of differing driver factors as contributors to accidents. This group ranked "performance degraded by vibration" at the midpoint of the scale of driver-related factors (above other factors ranked by the overall group, which were "stress due to personal problems," "under the influence of drugs," "sick or physically impaired," and "anti-social attitude"). Likewise, the overall group estimated that nearly five percent of the health problems of career truck drivers are significantly contributed to by the fact that drivers are exposed to strong ride vibrations. Accordingly, while the human performance experts involved in the vibration subject are rigorous in not drawing firm conclusions from the available data on the truck ride vibration issue, the overall group judgments would indicate reservations that vibration may play a role in five percent of career driver health problems.

The expressions of judgment on the part of the overall group of conference participants shows that vibration-related factors are given the lowest priority among those vehicle and driver factors which are seen to contribute to accidents, whereas it is of intermediate importance as a highway concern. Perhaps the one group which was most concerned about the likely significance of a factor which was in its own area of expertise was the highway group. The highway experts ranked the factor "distributed and localized roughness" slightly higher than five other highway factors which might contribute to truck accidents. What may be of greater significance, however, is the concern expressed by these experts with the continuing deterioration in the pavement quality of the nation's road system. The highway group chose to submit for endorsement by the conferees a statement projecting an increase in the vibration exposure of truck drivers if the deterioration in the road system is permitted to continue uncorrected. The statement, which accepted the data generated in this project relating truck ride vibration to the actual roughness condition of road surfaces, received unanimous agreement from the conferees.

The pavement roughness condition was given attention throughout the conference in terms of both the random, small amplitude, roughness of the surface (which accounts for much of the more-or-less continuous background vibration which truck drivers experience) and the severe localized pavement faults which may momentarily jar the driver. While the relative importance of each type of roughness in the overall safety picture is not at all understood, severe vibration as may result from localized pavement faults was viewed as a possible mechanism affecting safety by disturbing the driver's ability to maintain control of the vehicle.

Fatigue was identified as the other most likely causal linkage between vibration and safety. It was recognized that vibration exposure may both increase driver vigilance, on the short term, as well as diminish vigilance as fatigue sets in. In addition, it would appear that many of the other stress factors characteristic of long-haul truck driving could act, synergistically, with vibration to influence the state of fatigue which may result. The question of fatigue, then, is seen as a very complex problem. This point of view was articulated in the consensus statement that read: "Any investigations into the relationship between truck ride vibrations and accident involvement must consider interactions between vibration and other factors contributing to fatigue."

The alternative route of looking to the accident record for evidence of a safety effect provides little information. Specifically, the accident data currently available are not sufficient to prove that any significant link between truck ride vibrations and accident involvement exists or does not exist. Although the data are inconclusive, they do provide guidance for recommending further work in this area. In general, the review of existing accident data implies that if ride vibrations play a significant role in highway safety, then the mechanisms involved are complex and involve interactions with other factors as in the case of fatigue. For the most part, the accident data were sufficient to reject the straightforward direct links between ride vibration and accident involvement, such as the loss of control due to inability to modulate foot controls.

Finally, there was concern among some of the experts that driver morbidity could reduce the proficiency of driving skills, thereby influencing safety. It was generally agreed that such an effect is possible, although there was no consensus that morbidity is, itself, produced by long-term exposure to truck ride vibrations.

4.2 Recommendations

In spite of a lack of evidence on the relationship between truck vibration and safety or health, nevertheless the group proffered recommendations to continue work on the subject. In some cases, they were willing to propose recommendations directed toward certain factions, while in other cases, no responsible faction would be identified. The following recommendations are drawn from the conference with some expansion and interpretation applied by the authors.

1) The SAE should be encouraged to develop Standards and Recommended Practices for the measurement and analysis of truck ride vibration data.

2) The ISO and ANSI writing groups should be encouraged to work on amendments to ISO 2631 and/or ANSI S3.18-1979 for application to the evaluation of truck driver vibration environments, with emphasis on the high-amplitude, short-duration transient accelerations.

3) Both the government and the trucking industry should be encouraged to continue research on measurement and characterization of the truck ride vibration environment, with emphasis on characterizing the long-term vibration exposure of truck drivers, including occurrences of short-duration, high-level transients.

4) The federal government should consider continuing research in the following areas:

   a) Effects of factors specific to the truck driving environment (vibration, noise, schedule, etc.) on driver fatigue, performance, safety, and health. The experimental simulator method is specifically identified as a recommended means to study these connections.

   b) Effects of road roughness on vehicle vibrations as may adversely affect ride, safety, and roadway deterioration.

   c) Effects of vibration on the long-term health of truck drivers.

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APPENDIX A

BACKGROUND DATA RELATED TO THE CONFERENCE ENTITLED "TRUCK RIDE QUALITY AND HIGHWAY SAFETY—IS THERE A CONNECTION?"

L. Segel and T.D. Gillespie

The purpose of this appendix is to document for the record the "what, where, when and how" of the conference which served as a key element of this project. The appendix contains four sections. The first section is titled "Conference Logistics" and summarizes the process by which the conference was organized. The second section identifies the 26 conferees and shows how they were grouped heterogeneously and homogeneously for purposes of discussion. The brief schedule provided to each conferee constitutes section three, with section four being the "Opinion Survey" which each conferee was asked to complete.

A.1 Conference Logistics

The subject conference was held at the Sheraton University Inn, in Ann Arbor, Michigan, on January 24, 25, and 26, 1982. The meeting culminated a sequence of steps related to its initial conceptualization, planning, and organization.

As indicated in the body of this report, the decision to hold a conference as a means of developing a desired body of conclusions and recommendations was made initially by FHWA staff. HSRI, on the other hand, was given the task of organizing the conference. In taking on this responsibility, it was agreed that HSRI would develop and submit (for approval) a conference plan presenting:

a) a proposed conference format, structure and agenda,

b) a proposed list of people to be invited, with reasons given for their selection,

c) draft letters of invitation to the conference, and

d) a proposed location and dates.

The required plan was developed during July and August of 1981, and outlined the basic concepts and principles to be employed. In the subsequent months, HSRI staff met periodically with its consultants (R. Lippett and K. Dannemiller) to work out the detailed structure and format of the conference, leading to the conference goals and design described in the body of this report.

The conference plan (as submitted to the FHWA in August, 1981) pointed out that prospective conferees fall into essentially three categories whose participation is desired because they:

1) possess substantive professional experience and knowledge regarding the fields of (a) motor vehicle vibration, (b) human response to whole-body vibration (over the short and long term), and (c) accident probabilities as influenced by driver (i) alertness, (ii) control capabilities, and (iii) physical and mental state,
2) have a substantial stake in the conclusions of the meeting regarding the relationship of truck ride quality to motor carrier safety, or
3) hold positions and responsibilities within Government which gives them substantial reasons for participating in the deliberations of the conference.

Persons falling into the first category were identified by HSRI staff primarily on the basis of (a) personal knowledge, (b) the recommendations of others, and (c) the evidence provided by publications. Prior to extending these individuals a formal invitation, they were contacted by phone to determine their interest and availability. The developed listing of prospective attendees (selected on the basis of their expertise) encompassed four categories of "experts," viz."

1) academicians,
2) researchers and scientists employed by the federal and state governments,
3) engineers and researchers employed in the private sector, and

4) engineers and researchers who are not members of subcategories (1), (2), or (3).

Although 27 individuals were initially identified as "experts" deserving of serious consideration in the selection process, the selection process itself (plus attritions due to illness, inclement weather, etc.) produced a total 13 conferees who, on the basis of the above-defined criteria, fall into the so-called "expert" category.

Whereas "experts" were approached individually, it was felt that special interest groups should be asked to select or appoint that individual who was best qualified to represent them. Initially, eight organizations were identified as deserving of consideration. At the time the conference actually took place, the following six organizations were represented:

1) Private Truck Council of America, Inc.
2) Motor Truck Manufacturers Division, Motor Vehicle Manufacturers Association
3) International Brotherhood of Teamsters, Chauffeurs, Warehousemen and Helpers of America
4) American Trucking Association, Inc.
5) Truck-Trailer Manufacturers Association
6) Truck Body and Equipment Association

The above six organizations accounted for seven of the total number of conferees present. Together with the 13 conferees invited as individuals and the six conferees representing units with the FHWA and the National Highway Traffic Safety Administration (NHTSA), they account for the 26 persons listed below as conference attendees. In addition to these 26 persons, Mr. Howard Anderson, formerly the FHWA Associate Administrator for Safety, was also present to provide some historical background at the opening session.

A.2 List of Conferees and Assignments to Heterogeneous and Homogeneous Groupings

The conferees, in alphabetical order, were:

Peter W. Arnberg, Road User and Vehicle Division, National Swedish Road and Traffic Research Institute, Fack, S-581 01, Linkoping, Sweden

James C. Barton, Senior Staff Engineer, Technical Center, Building A, Caterpillar Tractor Company, 100 N.E. Adams, Peoria, Illinois, 61629

Noble Bowie, Highway Safety Management Specialist, Bureau of Motor Carrier Safety, Federal Highway Administration, 400 Seventh Street, S.W., Washington, D.C., 20590

H. Keith Brewer, Accident Avoidance Division, Research and Development, National Highway Traffic Safety Administration, 400 Seventh Street, S.W., Washington, D.C., 20590

James Britell, Mechanical Engineer, Bureau of Motor Carrier Safety, Federal Highway Administration, 400 Seventh Street, S.W., Washington, D.C., 20590

Jeffery R. Davis, Chairman, Safety Committee, Private Truck Council of America, Inc., 1101 17th Street, N.W., Suite 1008, Washington, D.C., 20036 (Mail address: Air Products and Chemicals, Inc., P.O. Box 538, Allentown, Penn., 18105)

Leo DeFrain, Assistant Supervising Engineer, Testing and Research Laboratory, Michigan Department of Transportation, P. O. Box 30049, Lansing, Michigan, 48909

Charles R. Gielow, Vice President, Transportation and Safety, Roadway Express, Inc., P.O. Box 471, 1077 Gorge Boulevard, Akron, Ohio 44309

Ron Granning, Advisor to the President, Granning Suspensions, 13263 Merriman Road, Livonia, Michigan, 48150 (representing: Truck Body and Equipment Association, 5530 Wisconsin Avenue, Washington, D.C.)

Garth O. Hall, Director of Engineering, Bostrom Division, U.O.P., Inc., 133 W. Oregon Street, Box 2007, Milwaukee, Wisconsin, 53201

Marquis H. Harris, Chief Engineer, Product Evaluation and Development, GMC Truck and Coach Division, General Motors Corporation, 660 South Boulevard, East, Pontiac, Michigan, 48053

Rudolph R. Hegmon, Research Mechanical Engineer, Structures and Applied Mechanics Division, Office of Research. Federal Highway Administration, 400 Seventh Street, S.W., Washington, D.C., 20590

Henry R. Jex, Principal Research Engineer, Systems Technology, Inc., 13766 South Hawthorne Boulevard, Hawthorne, California, 90250

John J. Killilee, Vice President, Safety, Consolidated Freightways, Inc., 175 Linfield Drive, Menlo Park, California, 94025

Paul C. Manwiller, Fleet Maintenance Manager, Air Products and Chemicals, Inc., P.O. Box 538, Allentown, Pennsylvania, 18105

Nick Mehta, Chief Engineer, International Harvester, 3301 Wayne Trace, P.O. Box 1109, Fort Wayne, Indiana, 46801

Phillipi R. Pierce, Research and Development, Fruehauf Division, P. O. Box 238, Detroit, Michigan, 48232 (Representing: Truck-Trailer Manufacturers Association, 2430 Pennsylvania Avenue, N.W., Washington, D.C.)

Warren Rheaume, Safety and Health Department, International Brotherhood of Teamsters, Chauffeurs, Warehousemen, and Helpers of America, 25 Louisiana Avenue, N.W., Washington, D.C. 20001

Fred R. Ross, Research Project Engineer, Division of Highways and Transportation Facilities, Wisconsin Department of Transportation, 3502 Kinsman Boulevard, P.O. Box 7878, Madison, Wisconsin, 53707

Gary W. Rossow, Programs Manager, Motor Truck Manufacturers Division, Motor Vehicle Manufacturers Association of the United States, Inc., 1909 K Street, N.W., Suite 300, Washington, D.C., 20006

Jack Sandover, Department of Human Sciences, University of Technology, Loughborough, Leicestershire, LE11 3TU, UNITED KINGDOM

Charles F. Scheffey, Director, Office of Research, Federal Highway Administration, 400 Seventh Street, S.W., Washington, D.C., 20590

Victor A. Suski, Automotive Engineer, Technical Services Division, American Trucking Associations, Inc., 1616 P Street, N.W., Washington, D.C. 20036

John G. Viner, Head, Protective Systems Group, Structures and Applied Mechanics Division, Office of Research, Federal Highway Administration, 400 Seventh Street, S.W., Washington, D.C. 20590

Henning E. Von Gierke, AFAMRL/BB, Director, Biodynamics and Bioengineering Division, Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 45433

Donald E. Wasserman, Research Engineer, National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Cincinnati, Ohio 45226

As indicated earlier, on Sunday evening and on Monday, January 24 and 25, respectively, the above listed conferees were seated randomly at tables to form the following heterogeneous groups:

Table 1: W. Rheaume, H. Jex, N. Mehta, J. Davis, L. DeFrain, J. Sandover

Table 2: M. Harris, J. Killilee, F. Ross, R. Granning

Table 3: D. Wasserman, G. Hall, V. Suski, J. Britell, J. Viner

Table 4: H. Von Gierke, J. Barton, C. Gielow, P. Pierce, R. Hegmon, K. Brewer

Table 5: P. Arnberg, G. Rossow, N. Bowie, C. Scheffey, P. Manwiller

(It should be noted that for the time that he was able to stay, Mr. H. Anderson joined the conferees seated at Table 2.)

On Tuesday, January 26, the following homogeneous groupings were formed:

Table 1: (Conferees concerned with driver performance, fatigue, health and welfare): W. Rheaume, D. Wasserman, H. Von Gierke, H. Jex, J. Sandover, P. Arnberg, J. Barton

Table 2 (Conferees concerned with truck design and driver isolation): N. Mehta, M. Harris, G. Hall, G. Rossow, P. Pierce, R. Granning, H. Brewer

Table 3 (Conferees concerned with trucking safety and productivity): N. Bowie, J. Britell, V. Suski, P. Manwiller, C. Gielow, J. Killilee, J. Davis

Table 4 (Conferees concerned with highway design and road roughness): L. DeFrain, F. Ross, J. Viner, C. Scheffey, R. Hegmon

Finally, it should be noted that last minute developments prevented four conferees (who had previously indicated that they would be present) from attending. These four individuals were the following:

1) Heinrich Dupuis, Arbeitsgruppe Anthropotechnik/Ergonomie, Institut fur Arbeits-and Socialmedizin, University of Mainz, FEDERAL REPUBLIC OF GERMANY

2) Michael Griffin, Institute for Sound and Vibration Research, Human Factors Research Unit, University of Southampton, UNITED KINGDOM

3) John C. Guignard, Naval Biodynamics Laboratory, New Orleans, Louisiana

4) Armand Bud Mayer, Jr., former driver for Yellow Freight, Saline, Michigan

A.3 CONFERENCE SCHEDULE

Sunday, January 24, 1982

7:30 p.m.	Registration of conference participants
8:00 p.m.	Introductions, welcome, overview
	Interview of Mr. Mayer and Mr. Anderson
	Table discussions and reports
9:45 p.m.	Adjourn

Monday, January 25, 1982

8:30 a.m.	Comments on conference feedback
	Report on "Opinion Survey"
	Overview of day's activities and desired outcomes
	Interview of panel representing the five constituencies
10:15 a.m.	Coffee break
	Overview of the vibration-safety relationship
	Discussions regarding the information to be presented
	Presentation - What is the truck vibration environment?
	Group discussions regarding justifiable generalizations
12:30 p.m.	Lunch
1:30 p.m.	Feedback on group efforts
	Presentation - How vibration affects the driver
	Group discussions......
3:15 p.m.	Coffee break
	Presentation - What the accident record tells us
	Group discussions.....
	Ride Opinion Survey
	Summary of where we stand and Tuesday's objectives
	End of day evaluation
5:00 p.m.	Adjourn

Tuesday, January 26, 1982

8:30 a.m.	Feedback on conference evaluation
	Feedback on Opinion Survey
	Revision, validation and prioritizing of Monday's generalizations
10:15 a.m.	Coffee break
	Identify knowledge gaps, desirable group actions, etc.
	Group reports
12:30 p.m.	Lunch
1:30 p.m.	Feedback on the degree of consensus
	Further group discussions
	Comments by sponsors
3:30 p.m.	Adjourn

A.4

OPINION SURVEY

FHWA TRUCK RIDE QUALITY CONFERENCE

NAME ____________________

Instructions - Part 1

Listed below are a number of selected factors which may contribute to truck accidents. Since we will later attempt to place truck ride factors in the context of the overall truck safety problem, we wish first to establish your view of the likely ranking of safety factors other than ride.

Please assign a rank order to the factors, reflecting your view of their relative importance as contributors to accidents. Simply place the letter designating each factor on the ranking list at the desired level. For example, if you suspect that tire blowout is the most important vehicle factor among the factors listed, place the letter "A" next to the rank "1". You may find it convenient to fill out the rank lists by immediately placing the most and least important factors at the top and bottom, respectively, of the list and then proceeding to fill in the factors of intermediate importance.

Please note that there are no "right" answers to this survey. Further, we recognize that you may have very little information or experience from which to draw your ranking choices.

VEHICLE FACTORS

A) Tire Blowout
B) Poor Tire Traction
C) Poor Maintenance of Brakes Suspension, etc.
D) Excessive or Poorly Distributed Load
E) Poor Inherent Braking Performance
F) Poor Roll Stability
G) Poor Steering Control
H) Poor Truck Conspicuity

RANKING

1. _______
2. _______
3. _______
4. _______
5. _______
6. _______
7. _______
8. _______

HIGHWAY FACTORS

A) Slippery Pavement
B) Poor Interchange Design
C) Inadequate Bank on Curves
D) Narrow Lane Width
E) Poor Signing
F) Poor Shoulders (Dropoffs, etc.)
G) Inadequate Sight Distance
H) Long or Excessive Grades

RANKING

1.
2.
3.
4.
5.
6.
7.
8.

TRUCK DRIVER FACTORS

A) Under Infl. of Alcohol
B) Aggressive Driving Tactics (Tailgating, Speeding, etc.)
C) Under Infl. of Drugs
D) Inexperience
E) Sick or Physically Impaired
F) Inadequately Trained
G) Stress Due to Personal Problems
H) Anti-Social Attitude

RANKING

1.
2.
3.
4.
5.
6.
7.
8.

OPINION SURVEY

FHWA TRUCK RIDE QUALITY CONFERENCE

Instructions - Part 2

Please answer the following questions by checking that box which most represents your view (or your best guess).

What fraction of the total number of truck accidents would you say are significantly contributed to by the fact that the truck exhibits strong ride vibrations?

☐ less than 1%
☐ 1 to 2%
☐ 2 to 5%
☐ 5 to 10%
☐ 10 to 20%
☐ 20 to 50%
☐ Over 50%

What fraction of the health problems suffered by career truck drivers would you say are significantly contributed to by the fact that the trucks which they drive exhibit strong ride vibrations?

☐ less than 1%
☐ 1 to 2%
☐ 2 to 5%
☐ 5 to 10%
☐ 10 to 20%
☐ 20 to 50%
☐ Over 50%

What fraction of the total freight damage experienced during the cartage of goods by motor truck is caused by mechanical vibration while the vehicle is underway? (As opposed to being caused, for example, by mishandling at the dock, improper blocking of the load, water damage, etc.)

☐ less than 1%　☐ 1 to 2%　☐ 2 to 5%　☐ 5 to 10%

☐ 10 to 20%　☐ 20 to 50%　☐ Over 50%

Vehicles need maintenance because components wear and deteriorate with time. What fraction of the wear and deterioration of truck components would you say occurs as a result of mechanical vibration?

☐ less than 1%　☐ 1 to 2%　☐ 2 to 5%　☐ 5 to 10%

☐ 10 to 20%　☐ 20 to 50%　☐ Over 50%

APPENDIX B

EXPERIMENTAL MEASUREMENTS OF THE RELATIONSHIP BETWEEN TRUCK RIDE VIBRATION AND ROAD ROUGHNESS

M.W. Sayers and T.D. Gillespie

B.1 Introduction

Road roughness is a primary excitation source of truck ride vibration, yet no data exist is the literature to demonstrate that relationship or quantify its sensitivity. The objective in this experimental study was to obtain concurrent measurements of road roughness level on a selection of roads, using the best available current technology, along with measurements of the ride vibrations of a typical commercial vehicle operating on those roads, to demonstrate what relationship exists.

B.2 Experimental Method

A 1980 GMC cab-over-engine (COE) tractor and 45-foot van trailer were selected as the test vehicle (see Fig. B.1). The tractor was a two-axle vehicle, 142 inches in wheelbase, with an 86-inch aluminum sleeper cab. The front axle had a 10,860-lb gross axle weight rating with 54-inch taper leaf suspension. The rear axle was rated at 19,040 lbs and had a 51-inch flat leaf suspension with auxiliary springs. The tires were of bias-ply construction, size 10.00x20, load range F. With the exception of the front left tire, all wheels on the tractor were balanced and set up to minimize rolling force variations. By this means, the potential for randomly phased wheel effects to add scatter to the desired relationship was minimized. The trailer was a 45-foot tandem-axle van semitrailer manufactured by the Fruehauf Corporation. The trailer suspension incorporated three 40-inch taper leafs at each wheel position with equalization between axles.

The combination vehicle was tested both with the trailer empty and loaded with steel ballast located over the kingpin and trailer tandem. The axle loading conditions were:

Axle	Empty	Loaded
Tractor Front	9,200 lb	9,200 lb
Tractor Rear	8,100	17,300
Trailer Tandem	8,400	26,500

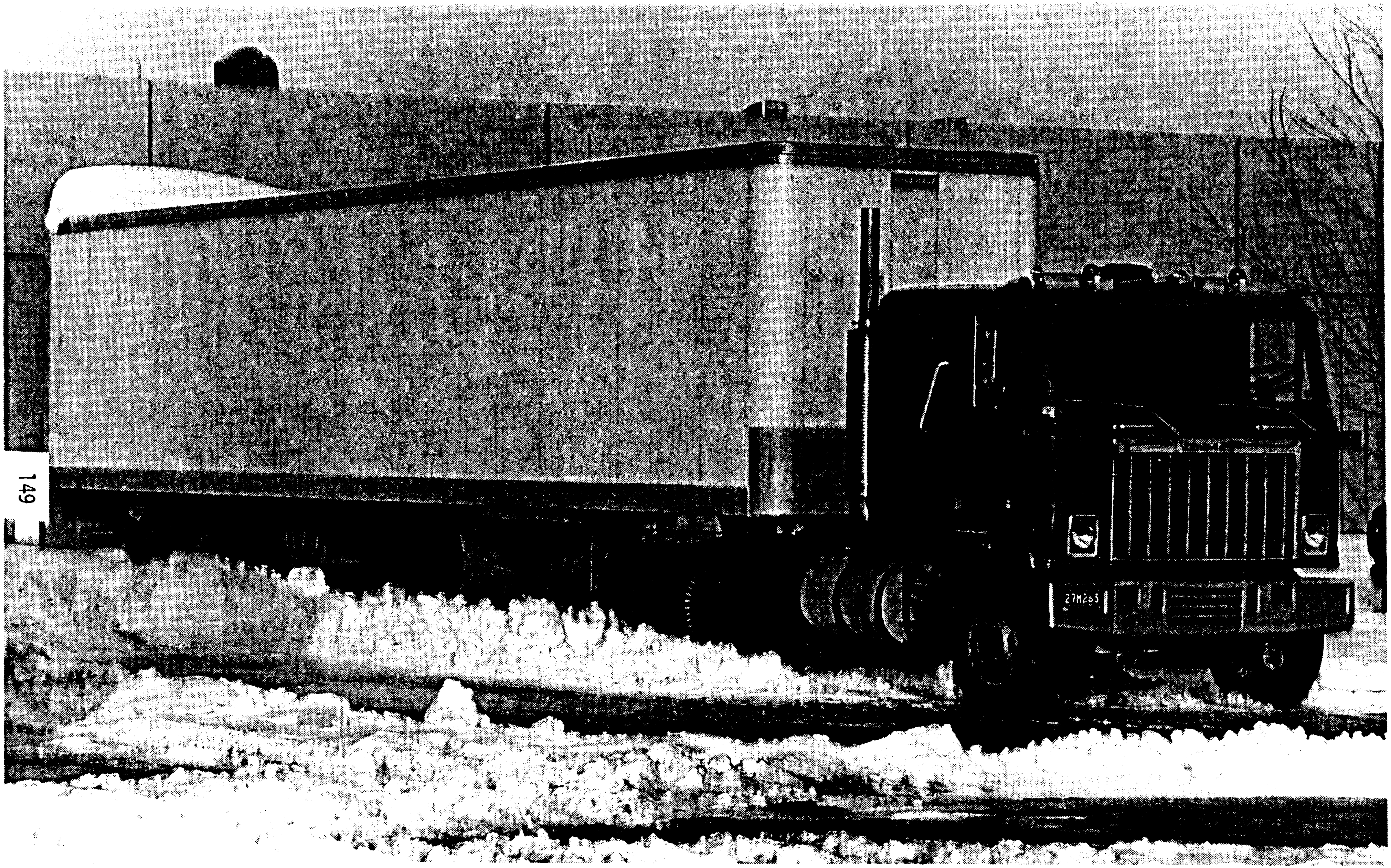

Figure B.1. GMC cab-over-engine test tractor with Fruehauf van trailer

The tractor was instrumented with accelerometers on the cab, along with the necessary signal conditioning and recording equipment. As shown in Figure B.2, five accelerometers were used to obtain seat interface vertical and fore/aft, cab floor vertical at the forward and aft positions, and cab floor fore/aft. For the remainder of this appendix, the accelerations at these five locations are called SZ, SX, FZ, RZ, and FX, respectively, as shown in the figure. The cab floor accelerometers were Entran piezoresistive strain gauge types (± 10 g range, 150 Hz bandwidth) obtained from the STI Ride Quality Instrumentation Package prepared under Contract DOT-FH-11-9513. The seat interface accelerometers were ± 5 g piezoresistive units mounted in an SAE J1013 rubber seat pad, which was a part of an Endevco RM-1 Ride Meter borrowed from FHWA for these tests. The accelerometer outputs were connected through an HSRI general-purpose amplifier/controller to an FM magnetic tape recorder. The amplifier/controller allowed convenient re-scaling of the accelerometer signals for different test conditions, and produced a control signal indicating test status, along with calibration reference voltages. The signals were recorded in analog format on a Honeywell 5600C FM magnetic tape recorder using the IRIG Intermediate Band at 1-7/8 ips (3.38K Hz center frequency) which provides 0-625 Hz bandwidth with 40 db dynamic range. Test identification was entered on the voice track of the tape recorder.

Ten road test sites, each approximately one mile in length, were selected in the vicinity of Ann Arbor, Michigan. The sites, identified in Table B.1, were known from prior research to cover the full spectrum of roughness levels of interest. The rougher road sections included the typical pavement distress features of cracking, faulting, and patching.

Ride tests with the tractor-semitrailer were conducted on all ten test sites in both the empty and loaded condition. At the test site, the vehicle was driven at constant speed through the section while recording data continuously, thus acquiring nominally 60 seconds of recorded measurements on each site. The vehicle was driven at the posted speed limit on each test section. Additional tests at 35, 40, 45, and 50 mph were made at three of the sites with the loaded vehicle in order

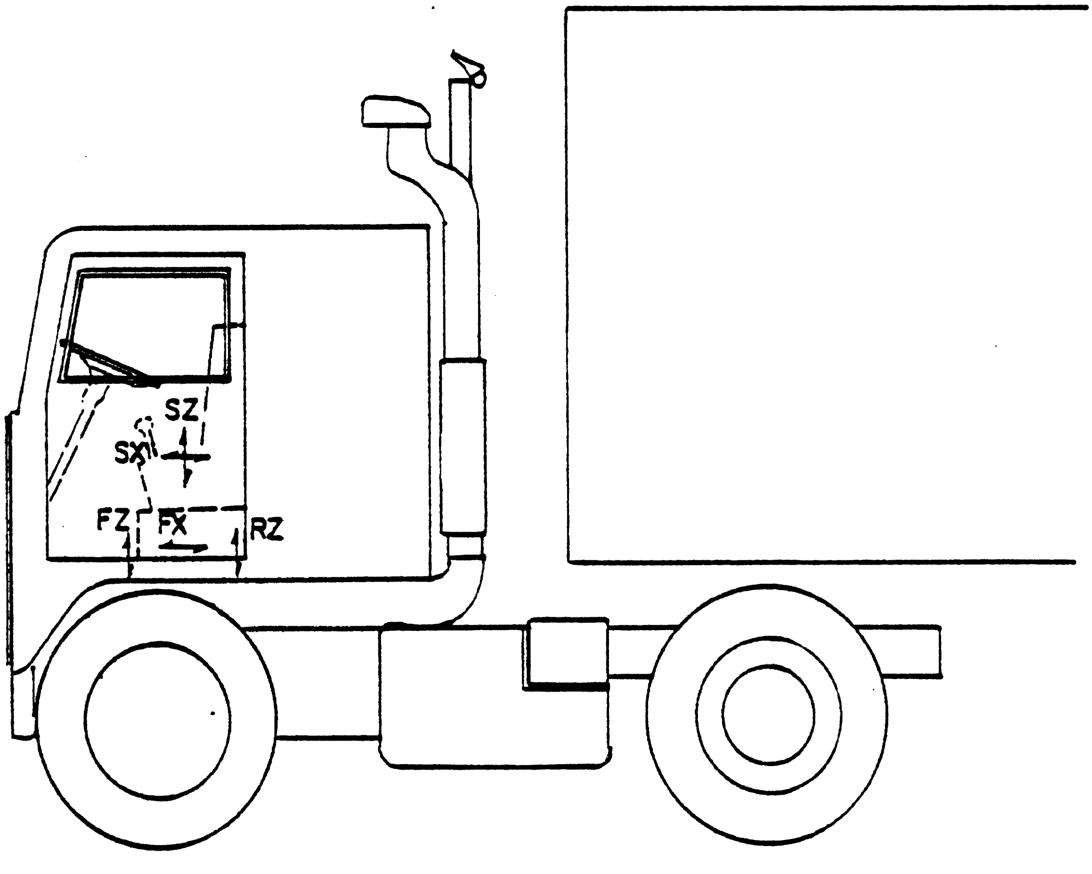

Figure B.2. Accelerometer names and locations in the test tractor.

Table B.1. Road Test Sites

Site No.	Speed Limit (mph)	Roughness RARV at Test Speed (in/sec)	Roughness Approximate PSI	Surface Type	Description	Location
1	55	.78	4.1	Bit.	Very smooth and level	I94, East (MP 180-181)
2	50	1.05	3.8	Bit.	Smooth and rolling	North Territorial Road, East, Dixboro to Tower Rd.
3	50	1.51	3.2	Bit.	Moderately smooth with occasional cracks & faults	Plymouth Rd., West from Curtis Rd.
4	45	1.57	3.2	Bit.	Patched and rolling	Curtis Rd., South from North Territorial
5	45	2.90	1.6	Bit.	Heavily patched with extensive tar strips	Ford Rd., West from M14 Exit
6	55	1.31	3.5	PCC	New construction, smooth	M14, East (MP 11-12)
7	55	1.44	3.3	PCC	New construction, rough	M14, East (MP 16-17)
8	55	1.87	2.8	PCC	Slightly cracked & faulted	M14, East Wagner Rd. to Miller Rd.
9	55	2.43	2.2	PCC	Moderately cracked & faulted	Route 23, South (MP 40-39)
10	55	2.72	1.8	PCC	Severe cracking & joint faulting with some patching	I94, West (MP 179-178)

to obtain data showing more directly the relationship between truck vibration level and operating speed. Due to technical difficulties, the data at various speeds on one test site are not considered valid and are hence not included in these test results.

Within ten days of the on-road truck tests, the vertical profiles of the left- and right-wheel track were measured for each road site by personnel from K.J. Law, Inc., with their Model 690D Digital Surface Dynamics Road Profilometer, which is representative of the state-of-the-art in profile measurement technology. It consists of a van equipped with two auxiliary spring-loaded follower wheels that contact the road in the two wheel tracks (60 inches apart). Displacements of these follower wheels are transduced with potentiometers. Movement of the sprung mass of the van is detected immediately above each follower wheel by vertically-oriented accelerometers. The van also contains a PDP 11 minicomputer that samples the transducer signals, numerically doubly integrates the accelerometer signals to yield the position of the van body immediately above the follower wheels, and then adds the follower-wheel deflections to yield the road elevation at each follower wheel position. A three-pole Butterworth high-pass filter is employed by the computer to reduce low-frequency errors. During the profile measurements, the cut-off frequency of this filter was set at the frequency corresponding to a 300-foot wavelength (0.27 Hz at 55 mph). Measurements of both wheel track elevations are made at intervals of about one inch. The samples are averaged over a length of 12 inches, to reduce aliasing, and the averages are then stored on digital tape at intervals of six inches (161 Hz at 55 mph).

B.3 Data Analysis

Truck Ride Data. The analog recordings obtained on the truck were played back in the HSRI laboratory into the STI/FHWA Truck Dynamics Instrumentation System in order to digitize them. At this time, each channel was filtered by a 50-Hz single-pole, low-pass filter to prevent aliasing at the sample frequency of 300 Hz. The digital tape was taken to the University's Michigan Terminal System (MTS) computer system and converted into a more convenient format for statistical analyses. During this conversion process, the control channel was computer monitored so that data for each test were properly isolated from non-test data, scaled in engineering units (g's), and then copied to labeled files for later access with the MTS computer. In addition, the mean value of each signal was removed. Trend removal was tried, and as expected, was quickly found to be unnecessary due to the length of the tests.

Thirteen numerics, summarized in Table B.2, were calculated for each variable. Also, each signal was transformed into the frequency domain for calculations of Power Spectral Densities (PSD's). The frequency transformations were performed by first "padding" the records with zeros so that the total number of samples became a power of two (either 16384 or 32768 for these tests), and then using a conventional FFT program to transform the whole record. Adjacent raw spectral values were averaged together to yield a final frequency resolution of 0.15 Hz. Depending on test length, either 8 or 16 adjacent raw values were averaged to yield each final PSD value. In addition, the raw PSD values were integrated over 1/3 octave bands, with center frequencies starting at 1.0 Hz and increasing by a factor of 1.260 up to 80.6 Hz, to yield 20 partial mean square values. After weighting these numbers according to the ISO vibration standard summarized in Table B.3, they were summed. The square root of the resulting weighted mean square is the ISO numeric listed in Table B.2. Note that the ISO weighting method reduces the significance of higher-frequency vibrations, and shows the highest sensitivity to vertical vibrations (FZ, RZ, SZ) between 4-8 Hz, and to fore/aft vibrations between 1-2 Hz.

Road Roughness Data. Processing of road profiles can yield a tremendous amount of information which can sometimes be overwhelming. Therefore, different possible descriptions were considered so that the most appropriate one, relative to truck ride, could be selected. Figure B.3 shows five of the many possible statistical representations of one road section. The actual measures of the left- and right-wheel track elevations can be used to define two different independent variables:

Table B.2. Numerics Calculated for Each Acceleration Signal

Name (Units)	Description
RMS (g)	Root-Mean-Square value
ISO (g)	ISO Weighted RMS Acceleration, as specified in ISO 2631-1978(E) Different weighting functions are used for vertical (FZ, RZ, SZ) and fore/aft (FX, SX) variables.
MAX (g)	Maximum value of signal during test
MIN (g)	Minimum (maximum negative) value of signal during test
MTT (g)	Mean Top Tenth - average of upper 10% of samples
MBT (g)	Mean Bottom Tenth - average of bottom 10% of samples
SODR (g)	Semi-Outer Decile range = (MTT-MBT)/2
CR + (-) CR -	Crest Ratios CR + = MTT/RMS CR - = MBT/RMS
+F2.0 (Hz) -F2.0	Shock rate index: frequency of positive crossings of +2.0 x RMS and -2.0 x RMS
FO + (Hz)	Frequency of positive zero crossings
ST/T (-)	Bandwidth index: $\sigma_T/\overline{T}$ where T = interval between zero crossings, σ_T = standard deviation of T, and $\overline{T}$ = mean value of T.

Table B.3. ISO Weighting Coefficients

Center Frequency	Vertical	Fore/Aft
1.00	.500	1.00
1.26	.560	1.00
1.59	.630	1.00
2.00	.710	1.00
2.52	.800	.800
3.17	.900	.630
4.00	1.00	.500
5.04	1.00	.400
6.35	1.00	.315
8.00	1.00	.250
10.1	.800	.200
12.7	.630	.160
16.0	.500	.125
20.2	.400	.100
25.4	.315	.080
32.0	.250	.063
40.3	.200	.050
50.8	.160	.040
64.0	.125	.0315
80.5	.100	.025

$$\text{ISO} = \sqrt{\sum_{i=1}^{20} (\text{RMS}_i \times \omega_i)^2}$$

Where

ω_i = the vertical or fore/aft weighting coefficient value shown for the i^{th} frequency band.

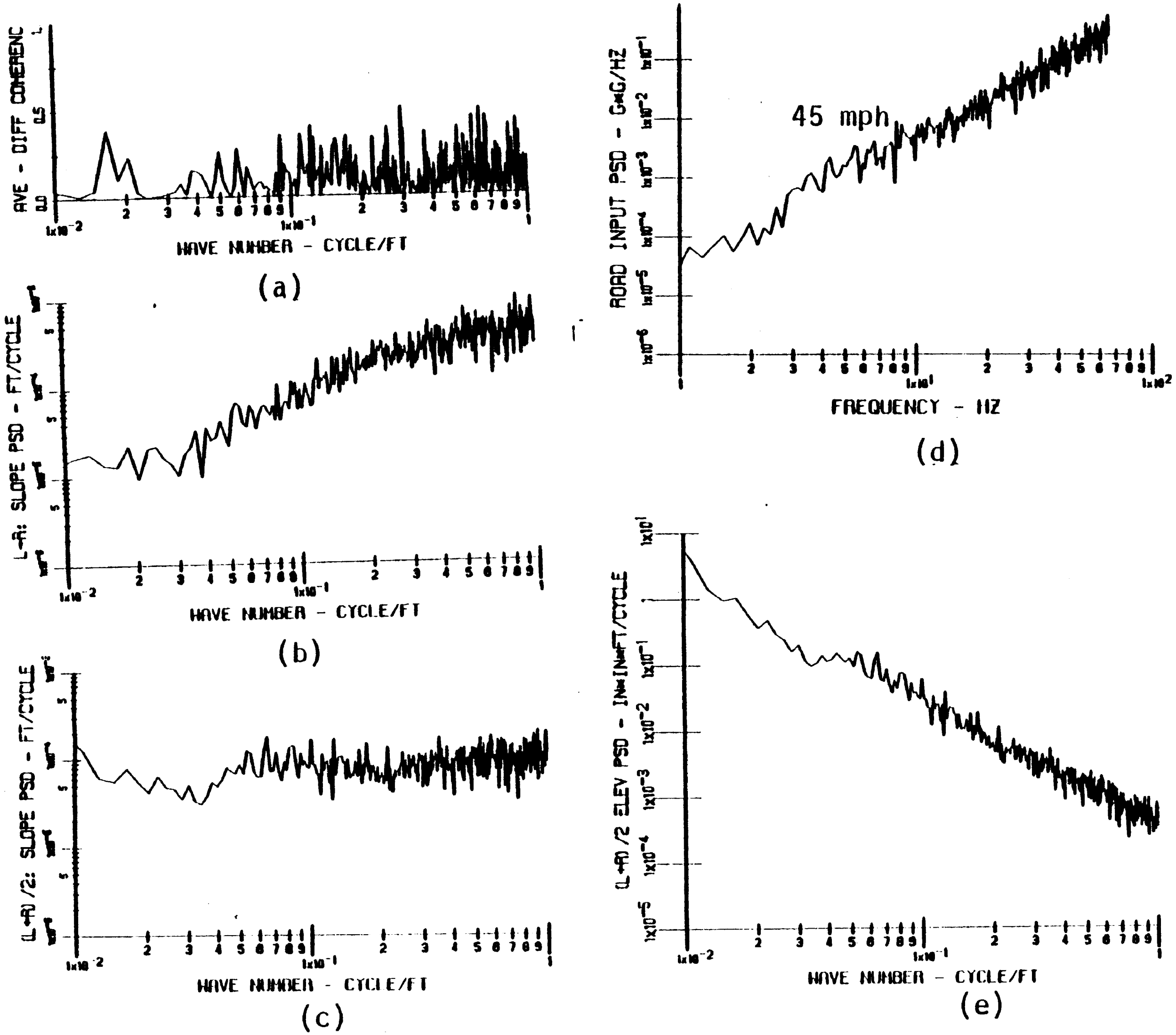

Figure B.3. Various representations of road site #5.

the average elevation (L+R)/2 and the elevation difference, (L-R). While the actual measured elevations L and R are correlated (when L increases, R has a tendency to increase also), the variables (L+R)/2 and (L-R) are more independent, as shown by the coherence function between them in Figure B.3a. Physically, the average (L+R)/2 profile excites vertical motions and pitching in a vehicle, while the difference (L-R) profile excites lateral motions and rolling in a vehicle. The PSD of the average (L+R)/2 profile—clearly of more interest in this study—is shown in three different formats in Figures B.3c, d, and e. Figure B.3e shows the simple elevation PSD, and possibly represents the most common format for presenting of road PSDs because it involves minimal processing and relates directly to the elevation measurements. As Figure B.3c shows, the PSD of the profile slope—the spatial derivative of elevation—is fairly uniform in amplitude over the range of wave numbers shown. This format is more convenient than the others when the intent is to compare different road sites, since improved scaling shows differences in PSD "signatures" more clearly, and because an approximate roughness numeric—the more-or-less constant PSD amplitude—can be read directly from the plot. In this example, the approximate amplitude is 1.2 x 10^{-4} ft/cycle.

In addition to the frequency-domain analyses, the profile data were used to produce single roughness numerics of the sort used by highway agencies. At this time, there is little standardization in the measurement of road roughness: different agencies may employ different measurement practices, devices, and data reduction methods to produce roughness statistics. The Present Serviceability Rating (PSR), as developed by AASHO in the 1950's, is the only widely recognized pavement rating scale.* Conceptually simple, PSR ranges from 0 to 5, with 5 being a perfect pavement site and 0 being impassable. Unfortunately, PSR is a subjective rating based on a lengthy process involving evaluation by a panel of highway experts. Present Serviceability Index (PSI) is often used instead, and is an estimate of PSR based on physical measurements of pavement properties that have been correlated to the PSR.

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*Carey, W.N., Jr. and Irick, P.E. "The Pavement Serviceability-Performance Concept," HRB Bulletin 250 (1960), pp. 40-58.

Based on prior research at HSRI, it is possible to estimate the PSI values for the surfaces, the values being given in Table B.1.

In practice, most measures of road roughness that are made in the world today are based on passenger cars or trailers equipped with roadmeter devices. The roadmeters transduce the suspension deflection between axle and body (rear axle for cars), and attempt to produce a measure of the accumulated deflection. When this measure is normalized by the time duration of the test, the result is an average of the suspension stroking speed, referred to mathematically as an Average Rectified Velocity (ARV). A more common practice among highway engineers is to normalize the accumulated deflection by the distance traveled during the test, and assign the units "Inches/Mile" (abbreviated I/M) to the resulting numeric. The two types of measures are related by the equation:

$$I/M = \frac{\text{ARV}}{\text{speed}}$$

The measures of roughness obtained by roadmeters are directly dependent on the test speed; thus, measurements are made at a standard test speed by most agencies. They are also dependent on the dynamic properties of the host vehicle and thus cannot be interpreted meaningfully unless related to some standard scale. Though no universally accepted standard scale exists for these measurements, a reference scale has been developed at HSRI for the specific purpose of calibrating roadmeter systems. The reference value is obtained from simulation of an HSRI quarter-car model operated over the measured road profile at the speed of interest. The output of the simulation has been denoted as a Reference ARV (RARV).

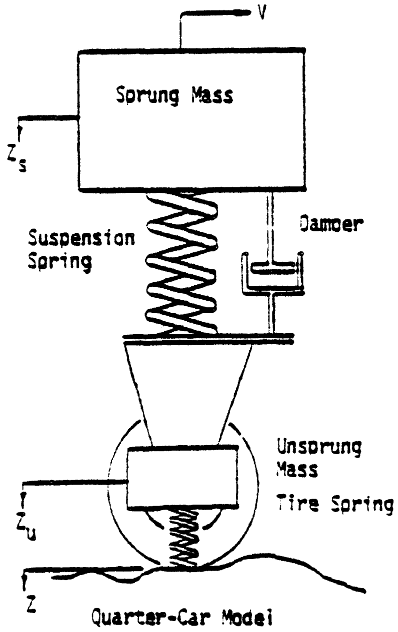
Figure B.4 defines the simulated quarter-car properties. The linear differential equations are numerically solved at each profile measurement, using the exact solution for assumed constant road slope between profile measurements. (That is, the elevation profile is assumed to be continuous and to linearly ramp from one measure to the next.) The RARV was calculated for each road test, using the proper combinations of measured profile and test speed.

$$\ddot{z}_s = K_2(z_u - z_s) + C(\dot{z}_u - \dot{z}_s)$$

$$\ddot{z}_u = \frac{1}{\mu}(z - z_u) - \ddot{z}_s/\mu$$

$$z = (L+R)/2$$

$$\mathrm{RARV} = \frac{1}{T}\int_0^T |\dot{z}_u - \dot{z}_s|\,dt$$



L,R = left-, right-track road elevations as functions of time

$K_1 = 653 \quad K_2 = 63.3 \quad C = 6.0 \quad \mu = 0.15$

Figure B.4. Calculation of RARV from HSRI quarter-car simulation.

Road/Vehicle Combination. Given the coincidence of data on road input and truck response, it is possible to explore the transmission of vibrations into the vehicle. The transmissibility of the truck cannot be calculated in a rigorous sense because the acceleration signals cannot be perfectly synchronized with the profile signals. Still, the transmissibility can be approximated by ratioing the output PSD (cab acceleration) by the input PSD, if the input PSD is in the right form. Accordingly, the profile signals were used to calculate PSDs of the road as an acceleration input to the truck, as seen by the truck when traversing the road at the test speed. Because the acceleration signals from the truck were padded with zeros to yield either 16384 or 32768 samples, the padded record lengths at the 300-Hz sampling frequency were correspondingly 54.6 and 109.2 seconds. The profile elevation signals were padded with zeros to result in the same time duration, based on a sampling rate calculated from the test speed:

$$f_s = 2 \text{ sample/ft} \times v \text{ ft/sec} \qquad \text{(B.1)}$$

where f_s is the sample frequency and v is the test speed, and

$$N = T \cdot f_s \qquad \text{(B.2)}$$

where N is the total number of points and T is the time duration of either 54.6 or 109.2 seconds. Zeros were added to the profile record to total N samples. Generally N was not a power of 2, so a less-efficient, mixed-radix FFT algorithm was employed which could operate for any number of points. The result of these manipulations is that the calculated road input PSD is a function of temporal frequency (Hz), and that the raw PSD values correspond to exactly the same frequency values as do the raw output acceleration PSDs. The elevation PSD values were re-scaled by a factor proportional to f^4, to convert to an acceleration input with the same units as the cab acceleration outputs—g^2/Hz. Figure B.3d shows such a PSD. After performing the same frequency averaging as was done for the cab accelerations, the output and input PSDs were ratioed, and the square root of this function—the approximate transmissibility—was plotted.

B.4 Results

Road Profile Inputs. The slope PSDs of the 10 pavement sections are presented in Figure B.5. The PCC sections are all seen to have similar frequency content for low (.01 cycle/ft) and high (1 cycle/ft) wave numbers, but differ at intermediate wave numbers. For wave numbers near 0.1 cycle/ft, the PSD level is a good indication of the overall roughness. The bituminous sections have more uniform PSDs for high wave numbers and, in most cases, the PSDs increase with the lower wave numbers. The PSDs of the two pavement types all differ in that the PCC PSDs show a variety of spectral peaks, indicative of periodicities in the pavement surfaces. Site #7, for example, shows spectral peaks at .07, .15, .22, .31, and .34 cycle/ft, which are the first five harmonics of a single periodic disturbance with a 13-foot spacing. The two roughest PCC surfaces (sites #9 and 10) show about 10 identical spectral peaks between .04 and 0.2 cycle/ft (5-25 foot wavelengths) which do not have such a simple harmonic relationship. All in all, the 10 surfaces are seen to represent a variety of highway road types with distinct signatures. One note here is that none of the 10 sites contains any singular disturbances, such as bridge or railroad crossings, and are relatively homogeneous across their lengths.

Truck Accelerations. All of the calculated numerics are presented in Tables B.4-B.9. While all 13 of the acceleration statistics are listed, in the interest of thoroughness, only the RMS accelerations are truly useful. The statistics MAX, MIN, MTT, MBT, SODR, CR+, CR-, +F2.0, and -F2.0 are all meaningful when describing singular events, particularly in the presence of continuous low-level excitation. But unless the tests include such events, these add little, if any, insight. For example, the tables show that in nearly every test, the average value of CR+ and CR- is about 1.75 (i.e., the mean top- and bottom-tenth levels can be estimated fairly accurately from the RMS value). Apparently, the truck has characteristic probability distributions for each variable that hardly change when traversing different roads, except for their scaling. While the distributions are not Gaussian or symmetric, they are sufficiently consistent from test to test that the simple RMS acceleration

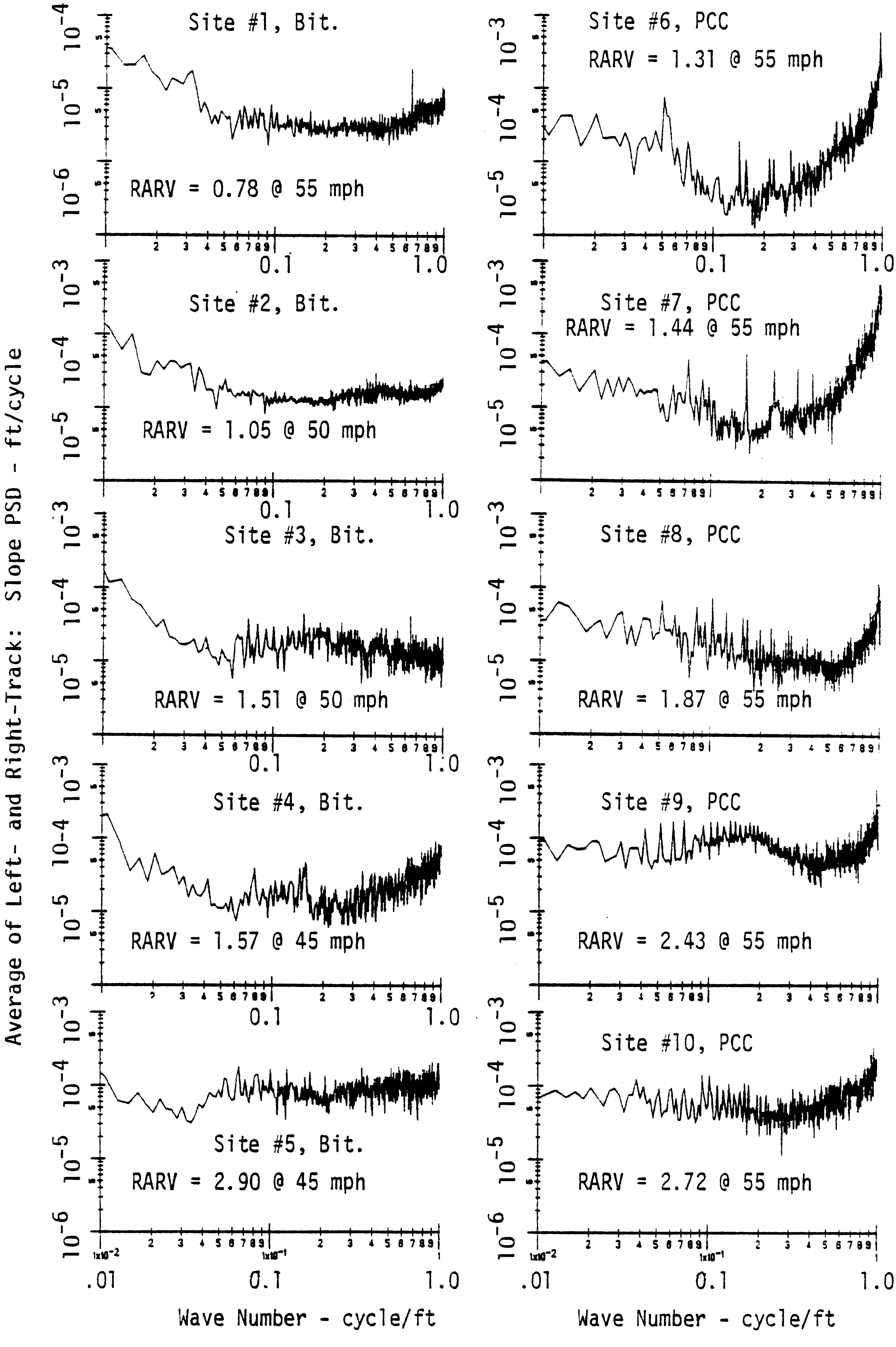


Figure B.5. PSDs of ten pavement sites used in test program.

Table B.4. Summary Acceleration Statistics for the Loaded Tractor-Semitrailer on Bituminous Road Surfaces.

I94 EAST, BETWEEN MILE POSTS 180 - 181, AT 55 MPH, LOADED TRUCK

ROAD ROUGHNESS RARV = 0.78 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.063	0.049	0.312	-0.238	0.118	-0.104	0.111	1.87	-1.64	2.89	0.90	18.9	1.05
RZ	0.060	0.044	0.307	-0.254	0.112	-0.100	0.106	1.85	-1.65	2.93	1.13	19.4	0.91
FX	0.046	0.015	0.227	-0.150	0.085	-0.077	0.081	1.84	-1.68	2.85	1.01	20.2	0.79
SZ	0.080	0.073	0.233	-0.156	0.146	-0.128	0.137	1.82	-1.59	0.68	0.0	4.2	0.48
SX	0.061	0.026	0.396	-0.367	0.104	-0.112	0.108	1.71	-1.84	1.50	0.94	18.7	0.92

N. TERRITORIAL AT 50 MPH, LOADED TRUCK

ROAD ROUGHNESS RARV = 1.05 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.083	0.054	0.359	-0.230	0.153	-0.134	0.144	1.85	-1.63	2.89	0.95	20.0	0.89
RZ	0.081	0.049	0.357	-0.224	0.149	-0.133	0.141	1.83	-1.64	3.05	1.06	20.0	0.77
FX	0.066	0.018	0.217	-0.174	0.116	-0.111	0.114	1.77	-1.70	2.52	1.32	18.7	0.60
SZ	0.079	0.069	0.224	-0.139	0.137	-0.122	0.129	1.74	-1.55	0.34	0.0	4.0	0.45
SX	0.083	0.033	0.416	-0.384	0.136	-0.152	0.144	1.64	-1.84	1.32	0.87	18.8	0.80

PLYMOUTH RD AT 50 MPH, LOADED TRUCK

ROAD ROUGHNESS RARV = 1.51 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.089	0.063	0.430	-0.308	0.162	-0.154	0.158	1.83	-1.74	2.53	1.10	20.3	0.99
RZ	0.081	0.055	0.344	-0.314	0.149	-0.142	0.146	1.83	-1.75	2.64	1.18	19.7	0.86
FX	0.062	0.017	0.452	-0.301	0.110	-0.110	0.110	1.78	-1.78	1.99	1.29	19.0	0.64
SZ	0.083	0.073	0.268	-0.151	0.146	-0.134	0.140	1.77	-1.62	0.48	0.0	4.3	0.51
SX	0.075	0.027	0.322	-0.345	0.132	-0.132	0.132	1.77	-1.78	2.05	1.29	19.4	0.76

CURTIS AT 45 MPH, LOADED TRUCK

ROAD ROUGHNESS RARV = 1.57 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.096	0.067	0.607	-0.324	0.177	-0.159	0.168	1.84	-1.66	2.55	0.88	21.0	0.96
RZ	0.093	0.063	0.526	-0.312	0.168	-0.158	0.163	1.80	-1.70	2.60	1.00	20.5	0.82
FX	0.070	0.019	0.286	-0.274	0.126	-0.122	0.124	1.79	-1.74	2.32	1.15	17.5	0.60
SZ	0.074	0.061	0.341	-0.146	0.129	-0.118	0.124	1.75	-1.61	0.42	0.0	4.1	0.58
SX	0.080	0.032	0.693	-0.457	0.132	-0.153	0.143	1.64	-1.91	1.28	0.88	18.0	0.79

FORD ROAD AT 45 MPH, LOADED TRUCK

ROAD ROUGHNESS RARV = 2.90 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.146	0.104	0.999	-0.698	0.260	-0.253	0.256	1.78	-1.73	2.17	1.07	18.8	0.93
RZ	0.136	0.094	0.989	-0.729	0.244	-0.238	0.241	1.78	-1.74	2.00	1.01	19.1	0.88
FX	0.097	0.031	0.420	-0.322	0.173	-0.172	0.172	1.78	-1.77	1.91	1.33	16.3	0.67
SZ	0.117	0.102	0.397	-0.206	0.197	-0.173	0.185	1.69	-1.48	0.49	0.0	4.5	0.57
SX	0.132	0.053	0.772	-0.790	0.221	-0.242	0.232	1.67	-1.83	1.62	1.07	17.0	0.87

Table B.5. Summary Acceleration Statistics for the Loaded Tractor-Semitrailer on PCC Road Surfaces.

M14 EAST. BETWEEN MILE POSTS 11 - 14. AT 55 MPH. LOADED

ROAD ROUGHNESS RARV = 1.31 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDDR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.104	0.087	0.394	-0.320	0.186	-0.173	0.180	1.79	-1.66	2.30	0.83	14.1	1.08
RZ	0.094	0.075	0.368	-0.284	0.169	-0.155	0.162	1.80	-1.65	2.67	1.00	15.6	1.05
FX	0.062	0.025	0.229	-0.223	0.109	-0.111	0.110	1.75	-1.78	2.28	1.23	16.5	0.89
SZ	0.102	0.093	0.310	-0.157	0.181	-0.142	0.161	1.77	-1.39	0.62	0.0	4.1	0.40
SX	0.109	0.045	0.765	-0.454	0.196	-0.191	0.193	1.80	-1.76	1.86	1.27	16.2	0.97

M-14 FROM THE 16 - 17 MILE POSTS. AT 55 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 1.44 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDDR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.090	0.069	0.320	-0.270	0.160	-0.157	0.158	1.79	-1.74	2.63	1.10	16.4	1.04
RZ	0.081	0.059	0.324	-0.271	0.143	-0.142	0.143	1.77	-1.75	2.22	1.04	16.7	0.96
FX	0.060	0.020	0.239	-0.207	0.106	-0.105	0.105	1.76	-1.74	2.36	1.10	17.4	0.82
SZ	0.094	0.084	0.254	-0.156	0.166	-0.143	0.154	1.76	-1.52	0.47	0.0	4.2	0.45
SX	0.083	0.038	0.317	-0.416	0.146	-0.148	0.147	1.76	-1.78	1.39	1.07	15.7	0.96

RTE. 23 SOUTH. BETWEEN MILE POSTS 40 - 39. AT 55 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 2.43 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDDR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.100	0.078	0.401	-0.367	0.178	-0.170	0.174	1.79	-1.70	2.09	0.88	14.9	1.09
RZ	0.090	0.068	0.415	-0.353	0.161	-0.155	0.158	1.78	-1.71	2.21	1.03	14.7	1.04
FX	0.061	0.024	0.235	-0.224	0.108	-0.106	0.107	1.78	-1.75	1.81	0.82	16.0	0.90
SZ	0.102	0.088	0.247	-0.158	0.173	-0.145	0.159	1.69	-1.42	0.42	0.0	4.0	0.53
SX	0.099	0.052	0.673	-0.472	0.171	-0.181	0.176	1.72	-1.82	1.75	0.91	13.0	1.07

I94 WEST. BETWEEN MILE POSTS 179 - 178. AT 55 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 2.72 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDDR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.130	0.099	0.576	-0.659	0.230	-0.234	0.232	1.77	-1.90	1.91	0.90	14.4	1.05
RZ	0.117	0.087	0.509	-0.656	0.205	-0.209	0.207	1.75	-1.79	1.37	0.87	15.2	0.95
FX	0.089	0.032	0.393	-0.286	0.157	-0.156	0.156	1.77	-1.75	1.76	1.10	15.2	0.78
SZ	0.119	0.101	0.568	-0.227	0.201	-0.194	0.197	1.69	-1.63	0.42	0.0	4.7	0.62
SX	0.112	0.058	0.414	-0.668	0.182	-0.207	0.194	1.63	-1.86	1.43	0.84	14.7	1.03

Table B.6. Summary Acceleration Statistics for the Loaded Tractor-Semitrailer on Bituminous Road Surfaces at Different Speeds.

I94 EAST. BETWEEN MILE POSTS 180 - 181. AT 35 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 0.49 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.055	0.041	0.322	-0.227	0.098	-0.094	0.096	1.79	-1.71	2.31	1.03	27.0	1.27
RZ	0.052	0.038	0.283	-0.248	0.090	-0.091	0.091	1.74	-1.76	2.16	1.15	24.9	1.10
FX	0.032	0.010	0.174	-0.154	0.055	-0.057	0.056	1.73	-1.81	2.08	1.05	18.7	0.72
SZ	0.070	0.063	0.322	-0.155	0.127	-0.121	0.124	1.82	-1.73	0.53	0.28	4.5	0.49
SX	0.043	0.016	0.288	-0.412	0.074	-0.077	0.075	1.72	-1.80	1.35	0.70	19.6	0.74

I94 EAST. BETWEEN MILE POSTS 180 - 181. AT 40 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 0.56 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.055	0.041	0.256	-0.200	0.098	-0.095	0.096	1.78	-1.73	2.22	0.99	25.7	1.12
RZ	0.054	0.038	0.276	-0.216	0.095	-0.094	0.095	1.76	-1.75	2.64	1.25	23.7	0.96
FX	0.034	0.010	0.148	-0.125	0.059	-0.063	0.061	1.71	-1.82	2.22	1.25	19.8	0.71
SZ	0.064	0.058	0.279	-0.143	0.114	-0.111	0.113	1.77	-1.72	0.43	0.26	4.8	0.56
SX	0.045	0.017	0.231	-0.376	0.078	-0.080	0.079	1.72	-1.78	1.70	1.11	19.6	0.87

I94 EAST. BETWEEN MILE POSTS 180 - 181. AT 45 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 0.63 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.056	0.040	0.260	-0.249	0.099	-0.096	0.098	1.79	-1.72	3.22	1.24	28.4	1.17
RZ	0.056	0.038	0.230	-0.267	0.099	-0.097	0.098	1.78	-1.74	3.44	1.28	25.8	1.00
FX	0.039	0.011	0.150	-0.125	0.067	-0.068	0.067	1.74	-1.75	2.74	1.31	20.1	0.69
SZ	0.069	0.063	0.237	-0.147	0.126	-0.115	0.120	1.83	-1.67	0.67	0.16	4.6	0.53
SX	0.049	0.018	0.257	-0.372	0.083	-0.090	0.086	1.68	-1.82	1.88	1.18	20.4	0.80

I94 EAST. BETWEEN MILE POSTS 180 - 181. AT 50 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 0.70 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.058	0.043	0.223	-0.204	0.104	-0.098	0.101	1.81	-1.71	2.67	1.15	21.6	0.98
RZ	0.054	0.038	0.193	-0.244	0.097	-0.093	0.095	1.79	-1.72	2.81	1.12	21.5	0.87
FX	0.041	0.012	0.163	-0.152	0.074	-0.071	0.072	1.80	-1.72	2.74	1.41	19.5	0.64
SZ	0.071	0.064	0.236	-0.142	0.128	-0.119	0.123	1.80	-1.66	0.54	0.0	4.6	0.52
SX	0.052	0.021	0.239	-0.357	0.088	-0.093	0.091	1.72	-1.81	2.27	1.23	20.6	0.82

Table B.7. Summary Acceleration Statistics for the Loaded Tractor-Semitrailer on PCC Road Surfaces at Different Speeds.

I94 WEST. BETWEEN MILE POSTS 179 - 178. AT 35 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 1.78 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.115	0.085	0.593	-0.549	0.214	-0.197	0.205	1.86	-1.71	2.16	0.75	17.0	1.18
RZ	0.103	0.074	0.510	-0.540	0.188	-0.176	0.182	1.83	-1.71	2.24	0.88	17.4	1.07
FX	0.070	0.027	0.437	-0.327	0.126	-0.126	0.126	1.81	-1.81	1.84	1.20	15.0	0.77
SZ	0.131	0.111	0.385	-0.281	0.211	-0.205	0.208	1.61	-1.56	0.22	0.02	3.8	0.52
SX	0.105	0.046	0.624	-0.718	0.174	-0.199	0.187	1.66	-1.90	1.53	0.98	15.1	0.93

I94 WEST. BETWEEN MILE POSTS 179 - 178. AT 40 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 2.02 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.116	0.088	0.649	-0.606	0.217	-0.198	0.207	1.87	-1.71	2.09	0.98	16.0	1.19
RZ	0.103	0.078	0.577	-0.454	0.193	-0.177	0.185	1.87	-1.72	2.53	0.98	16.4	1.06
FX	0.076	0.030	0.353	-0.326	0.136	-0.137	0.137	1.79	-1.80	1.78	1.04	14.1	0.85
SZ	0.135	0.117	0.383	-0.313	0.214	-0.210	0.212	1.59	-1.56	0.24	0.02	3.9	0.47
SX	0.121	0.055	0.646	-0.788	0.199	-0.234	0.216	1.64	-1.93	1.51	1.13	14.1	1.02

I94 WEST. BETWEEN MILE POSTS 179 - 178. AT 45 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 2.25 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.125	0.094	0.721	-0.503	0.229	-0.215	0.222	1.84	-1.72	2.28	1.09	16.2	1.15
RZ	0.112	0.082	0.572	-0.484	0.203	-0.195	0.199	1.80	-1.74	2.38	1.12	16.5	1.04
FX	0.082	0.029	0.420	-0.347	0.142	-0.153	0.148	1.73	-1.87	1.55	1.12	13.9	0.74
SZ	0.136	0.118	0.549	-0.263	0.218	-0.214	0.216	1.60	-1.57	0.30	0.0	3.9	0.46
SX	0.114	0.054	0.684	-0.637	0.189	-0.217	0.203	1.65	-1.90	1.62	1.06	15.2	0.99

I94 WEST. BETWEEN MILE POSTS 179 - 178. AT 50 MPH. LOADED TRUCK

ROAD ROUGHNESS RARV = 2.49 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SOOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.130	0.099	0.532	-0.570	0.235	-0.224	0.230	1.80	-1.72	2.39	1.01	14.4	0.99
RZ	0.118	0.086	0.470	-0.549	0.210	-0.210	0.210	1.78	-1.78	2.16	1.12	15.8	0.93
FX	0.086	0.031	0.377	-0.360	0.151	-0.157	0.154	1.76	-1.83	1.77	1.15	14.7	0.76
SZ	0.129	0.112	0.285	-0.271	0.201	-0.206	0.203	1.56	-1.60	0.28	0.03	4.3	0.53
SX	0.113	0.056	0.420	-0.685	0.182	-0.215	0.199	1.61	-1.90	1.40	0.98	14.8	1.02

Table B.8. Summary Acceleration Statistics for the Unloaded Tractor-Semitrailer on Bituminous Road Surfaces.

I94 EAST, 180 - 181, AT 55 MPH, UNLOADED

ROAD ROUGHNESS RARV = 0.78 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.070	0.043	0.274	-0.155	0.130	-0.110	0.120	1.86	-1.58	3.32	0.41	22.8	0.76
RZ	0.079	0.046	0.258	-0.261	0.135	-0.139	0.137	1.71	-1.76	2.40	1.51	21.5	0.66
FX	0.074	0.017	0.296	-0.225	0.128	-0.130	0.129	1.74	-1.78	2.10	1.18	17.3	0.59
SZ	0.048	0.038	0.155	-0.131	0.084	-0.082	0.083	1.77	-1.72	0.55	0.30	4.3	0.69
SX	0.077	0.020	0.601	-0.302	0.142	-0.126	0.134	1.86	-1.64	2.58	1.55	22.8	0.63

N. TERRITORIAL AT 50 MPH, UNLOADED

ROAD ROUGHNESS RARV = 1.05 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.083	0.052	0.359	-0.242	0.152	-0.135	0.144	1.84	-1.63	3.52	0.94	21.3	0.89
RZ	0.081	0.048	0.326	-0.260	0.148	-0.135	0.141	1.83	-1.66	4.11	1.15	21.5	0.82
FX	0.072	0.018	0.277	-0.204	0.131	-0.123	0.127	1.81	-1.70	2.42	1.25	17.8	0.64
SZ	0.065	0.052	0.235	-0.157	0.126	-0.111	0.118	1.93	-1.70	0.70	0.31	4.4	0.74
SX	0.090	0.022	0.749	-0.406	0.170	-0.143	0.157	1.90	-1.60	2.79	1.48	22.6	0.68

PLYMOUTH RD AT 50 MPH, UNLOADED

ROAD ROUGHNESS RARV = 1.51 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.091	0.063	0.389	-0.350	0.160	-0.159	0.159	1.77	-1.75	2.50	1.05	19.6	0.84
RZ	0.088	0.059	0.362	-0.371	0.152	-0.157	0.154	1.73	-1.79	2.22	1.19	19.2	0.77
FX	0.089	0.023	0.543	-0.318	0.161	-0.152	0.157	1.82	-1.72	1.70	1.02	14.7	0.59
SZ	0.061	0.049	0.287	-0.171	0.112	-0.104	0.108	1.83	-1.68	0.57	0.26	4.5	0.70
SX	0.098	0.023	0.704	-0.474	0.180	-0.168	0.174	1.84	-1.72	2.41	1.45	19.9	0.61

CURTIS AT 45 MPH, UNLOADED

ROAD ROUGHNESS RARV = 1.57 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.097	0.069	0.613	-0.434	0.176	-0.169	0.173	1.81	-1.74	2.25	0.96	19.9	0.91
RZ	0.094	0.064	0.625	-0.443	0.167	-0.166	0.167	1.78	-1.77	2.44	1.04	20.4	0.87
FX	0.084	0.022	0.480	-0.312	0.149	-0.147	0.148	1.77	-1.74	1.81	0.94	14.2	0.61
SZ	0.063	0.048	0.339	-0.167	0.113	-0.109	0.111	1.81	-1.74	0.35	0.21	4.6	0.74
SX	0.096	0.027	0.892	-0.448	0.185	-0.156	0.171	1.92	-1.61	2.71	1.40	19.1	0.71

FORD ROAD AT 45 MPH, UNLOADED

ROAD ROUGHNESS RARV = 2.90 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SDOR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.142	0.103	0.772	-0.574	0.259	-0.249	0.254	1.82	-1.75	2.22	1.25	18.4	0.87
RZ	0.137	0.096	0.755	-0.558	0.244	-0.246	0.245	1.78	-1.79	2.22	1.16	19.2	0.80
FX	0.130	0.039	0.710	-0.377	0.234	-0.223	0.228	1.79	-1.71	1.67	0.93	13.7	0.65
SZ	0.094	0.077	0.346	-0.220	0.170	-0.149	0.160	1.82	-1.60	0.61	0.13	4.9	0.72
SX	0.193	0.059	1.796	-0.832	0.370	-0.330	0.350	1.92	-1.71	2.41	1.70	20.1	0.69

Table B.9. Summary Acceleration Statistics for the Unloaded Tractor-Semitrailer on PCC Road Surfaces.

M14 EAST, 11 - 12, AT 55 MPH, UNLOADED

ROAD ROUGHNESS RARV = 1.31 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.094	0.072	0.330	-0.249	0.171	-0.154	0.163	1.82	-1.64	3.02	1.05	16.7	1.03
RZ	0.087	0.062	0.292	-0.296	0.154	-0.151	0.152	1.77	-1.73	2.27	1.19	18.5	0.91
FX	0.090	0.033	0.303	-0.277	0.154	-0.161	0.157	1.71	-1.80	1.49	0.98	13.4	0.80
SZ	0.089	0.077	0.298	-0.155	0.169	-0.131	0.150	1.89	-1.47	0.81	0.0	4.5	0.59
SX	0.126	0.049	0.986	-0.584	0.247	-0.188	0.217	1.96	-1.50	2.81	1.02	17.0	0.96

M14 EAST, 16 - 17, AT 55 MPH, UNLOADED

ROAD ROUGHNESS RARV = 1.44 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.091	0.068	0.337	-0.276	0.166	-0.152	0.159	1.82	-1.67	2.91	1.01	16.6	0.97
RZ	0.089	0.064	0.316	-0.289	0.158	-0.154	0.156	1.78	-1.74	2.45	1.19	16.8	0.93
FX	0.093	0.028	0.332	-0.325	0.164	-0.165	0.164	1.75	-1.77	1.65	1.13	14.3	0.70
SZ	0.078	0.066	0.208	-0.146	0.139	-0.121	0.130	1.79	-1.56	0.58	0.0	4.3	0.60
SX	0.112	0.036	0.819	-0.700	0.213	-0.177	0.195	1.91	-1.58	2.64	1.16	17.2	0.81

M14 EAST, WAGNER - MILLER, AT 55 MPH, UNLOADED

ROAD ROUGHNESS RARV = 1.87 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.103	0.081	0.385	-0.346	0.182	-0.177	0.179	1.77	-1.72	1.74	0.96	14.5	0.90
RZ	0.094	0.071	0.368	-0.323	0.167	-0.162	0.164	1.78	-1.73	1.88	0.99	14.7	0.86
FX	0.108	0.033	0.390	-0.278	0.197	-0.179	0.188	1.82	-1.66	1.92	0.86	12.0	0.61
SZ	0.085	0.072	0.255	-0.165	0.147	-0.134	0.141	1.73	-1.57	0.68	0.0	4.8	0.65
SX	0.141	0.047	1.034	-0.655	0.269	-0.226	0.247	1.90	-1.60	2.50	1.20	17.8	0.84

RTE. 23 SOUTH, 40 - 39, AT 55 MPH, UNLOADED

ROAD ROUGHNESS RARV = 2.43 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.109	0.081	0.657	-0.360	0.196	-0.187	0.191	1.80	-1.72	2.40	1.08	15.7	1.00
RZ	0.104	0.074	0.601	-0.443	0.184	-0.186	0.185	1.77	-1.79	2.19	1.32	16.3	0.97
FX	0.100	0.030	0.417	-0.327	0.180	-0.174	0.177	1.80	-1.75	1.96	1.23	14.6	0.73
SZ	0.084	0.066	0.263	-0.153	0.145	-0.126	0.136	1.71	-1.50	0.45	0.0	3.8	0.62
SX	0.131	0.038	1.037	-0.469	0.259	-0.211	0.235	1.98	-1.62	3.06	1.74	20.5	0.72

I94 WEST, 179 - 178, AT 55 MPH, UNLOADED

ROAD ROUGHNESS RARV = 2.72 IN/SEC

VAR	RMS (G'S)	ISO (G'S)	MAX (G'S)	MIN (G'S)	MTT (G'S)	MBT (G'S)	SODR (G'S)	CR+	CR-	+F2.0 (HZ)	-F2.0 (HZ)	FO+ (HZ)	ST/T
FZ	0.131	0.100	0.575	-0.574	0.236	-0.229	0.233	1.80	-1.75	1.97	1.02	14.4	0.99
RZ	0.126	0.093	0.594	-0.567	0.227	-0.224	0.225	1.80	-1.78	2.33	1.28	14.7	0.88
FX	0.125	0.037	0.481	-0.340	0.225	-0.213	0.219	1.80	-1.70	1.76	1.10	13.3	0.65
SZ	0.101	0.082	0.403	-0.251	0.169	-0.161	0.165	1.67	-1.58	0.42	0.21	4.1	0.66
SX	0.176	0.055	1.844	-0.743	0.342	-0.297	0.319	1.94	-1.69	2.90	1.49	19.2	0.70

does a very good job of predicting the other statistics. Hence, any regression analyses are not improved by adding the other statistics. Given the common knowledge that truck vibrations are broad band except on very smooth roads, the statistics F0+ and ST/S are of little use, and offer a poor second choice to PSDs. Before discussing the RMS and ISO statistics, it is helpful to observe the acceleration PSDs.

Figures B.6-B.16 show PSDs of four of the measured accelerations for a limited matrix covering the truck in loaded and unloaded state, smooth, moderate and rough roads, and bituminous (flexible) and PCC (rigid) constructions. Each PSD is plotted twice: once in a log-log format, to best illustrate the overall behavior, and once in a linear-linear format, to best show the frequency content of the mean-square acceleration (mean-square acceleration = area under PSD curve in a linear-linear plot). Some observations made from these figures, and others not shown, follow.

1) The seat accelerations (SX and SZ) are dominated by vibrations in the fairly narrow frequency band between 2-5 Hz in all cases.

2) The seat accelerations show wider bandwidth and more spectral peaks when the truck is in the unloaded state and when the road is a PCC pavement.

3) Effects of the rotating tire/wheel components (which occur at 7.8, 16, and 23 Hz at 55 mph; 7.0, 14, and 21 Hz at 50 mph; and at 6.4, 13, and 19 Hz at 45 mph) are the most noticeable on the smoother bituminous surfaces, particularly the third harmonic near 20 Hz. Forcing due to this harmonic is evident in all of the log-log plots for both floor and seat accelerations, although the linear plots show that it has negligible effect on the overall mean-square acceleration except on the smooth bituminous surfaces (Figs. B.6-B.9).

4) The floor accelerations often have frequency content up through 25 Hz, with many spectral peaks within that frequency range. More spectral peaks are noticeable on the

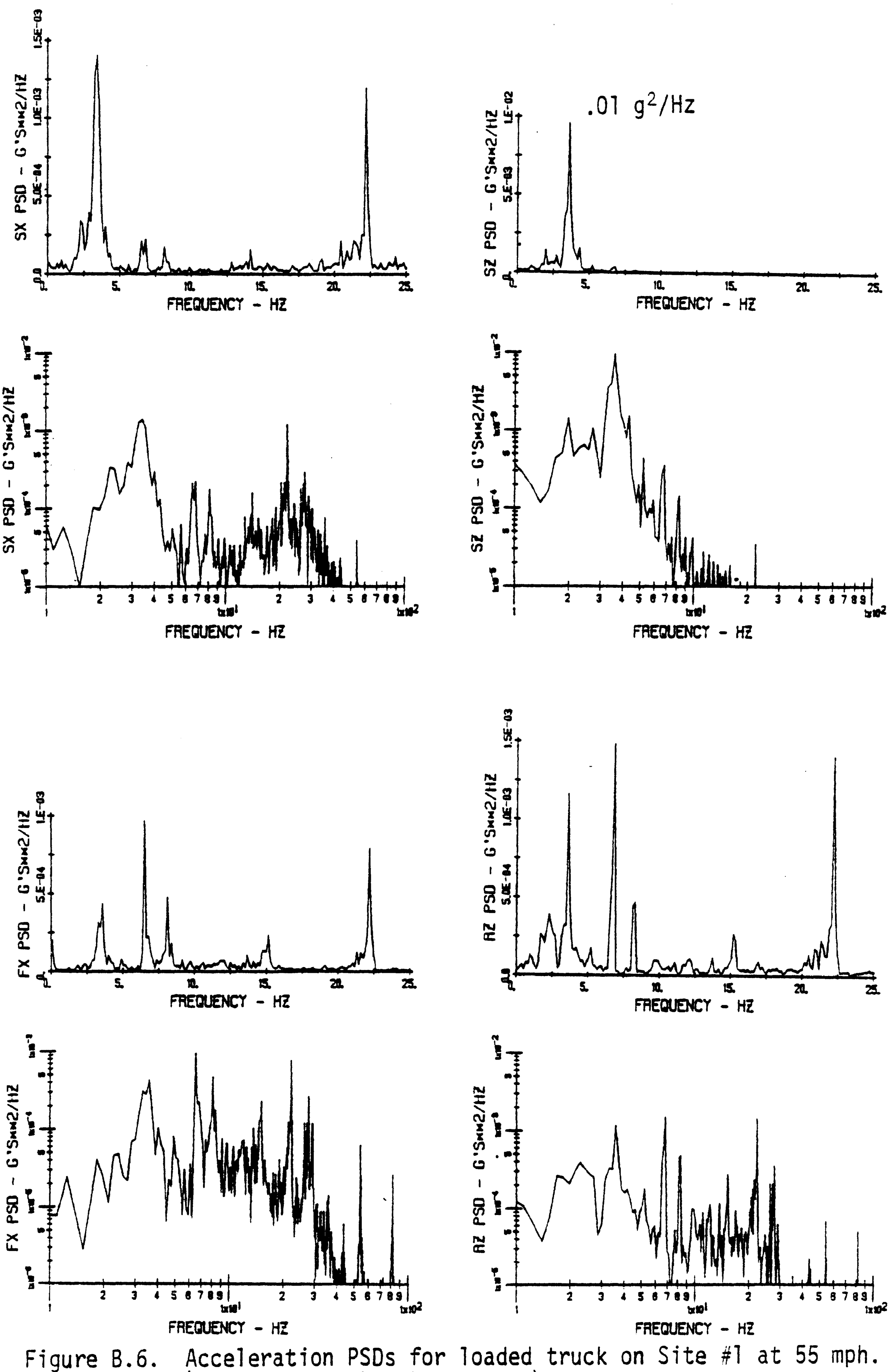


Figure B.6. Acceleration PSDs for loaded truck on Site #1 at 55 mph.
(Very smooth bituminous road)

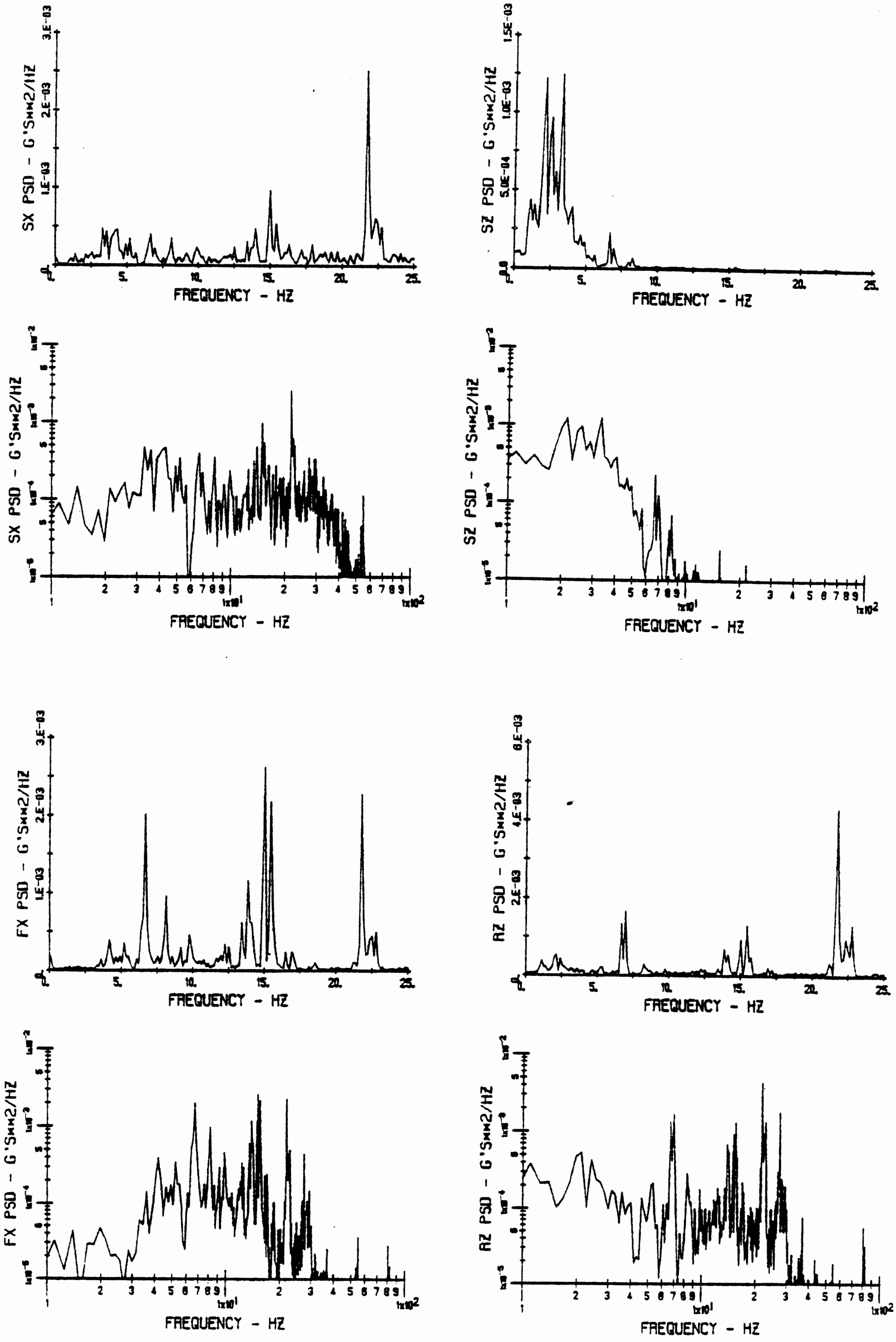


Figure B.7. Acceleration PSDs for unloaded truck on Site #1 at 55 mph.
(Very smooth bituminous road)

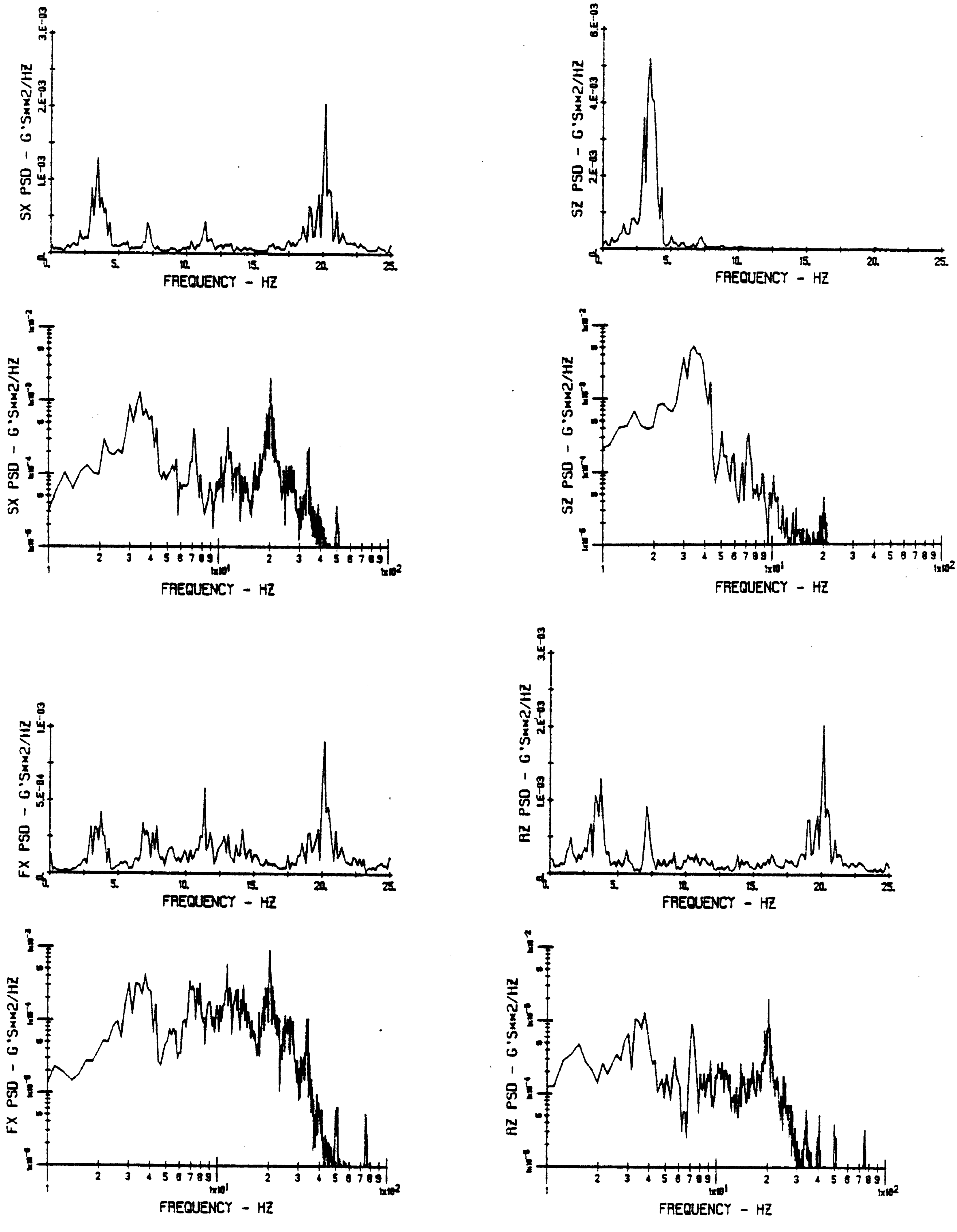


Figure B.8. Acceleration PSDs for loaded truck on Site #3 at 50 mph. (Moderately smooth bituminous road)

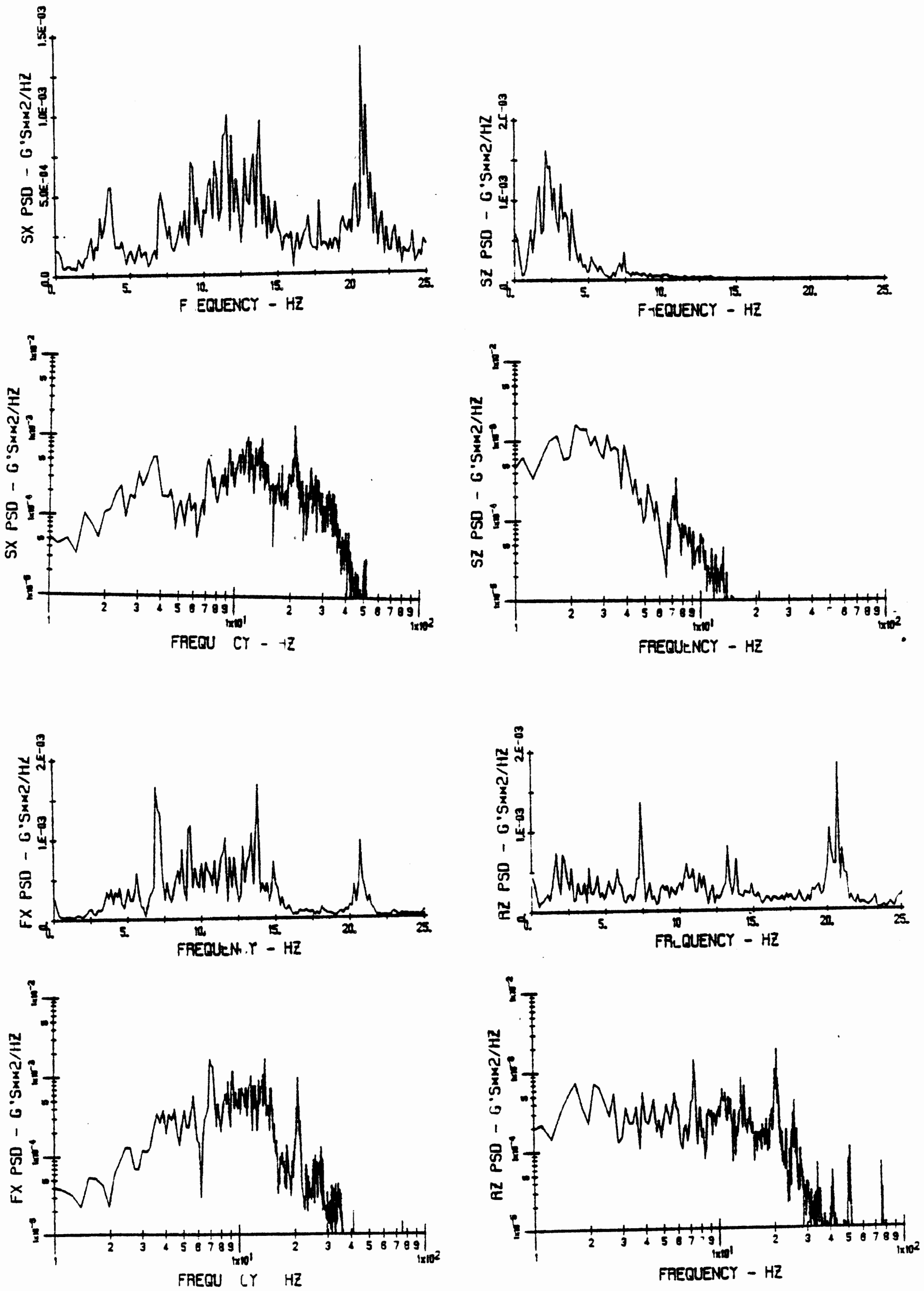


Figure B.9. Acceleration PSDs for unloaded truck on Site #3 at 50 mph. (Moderately smooth bituminous road)

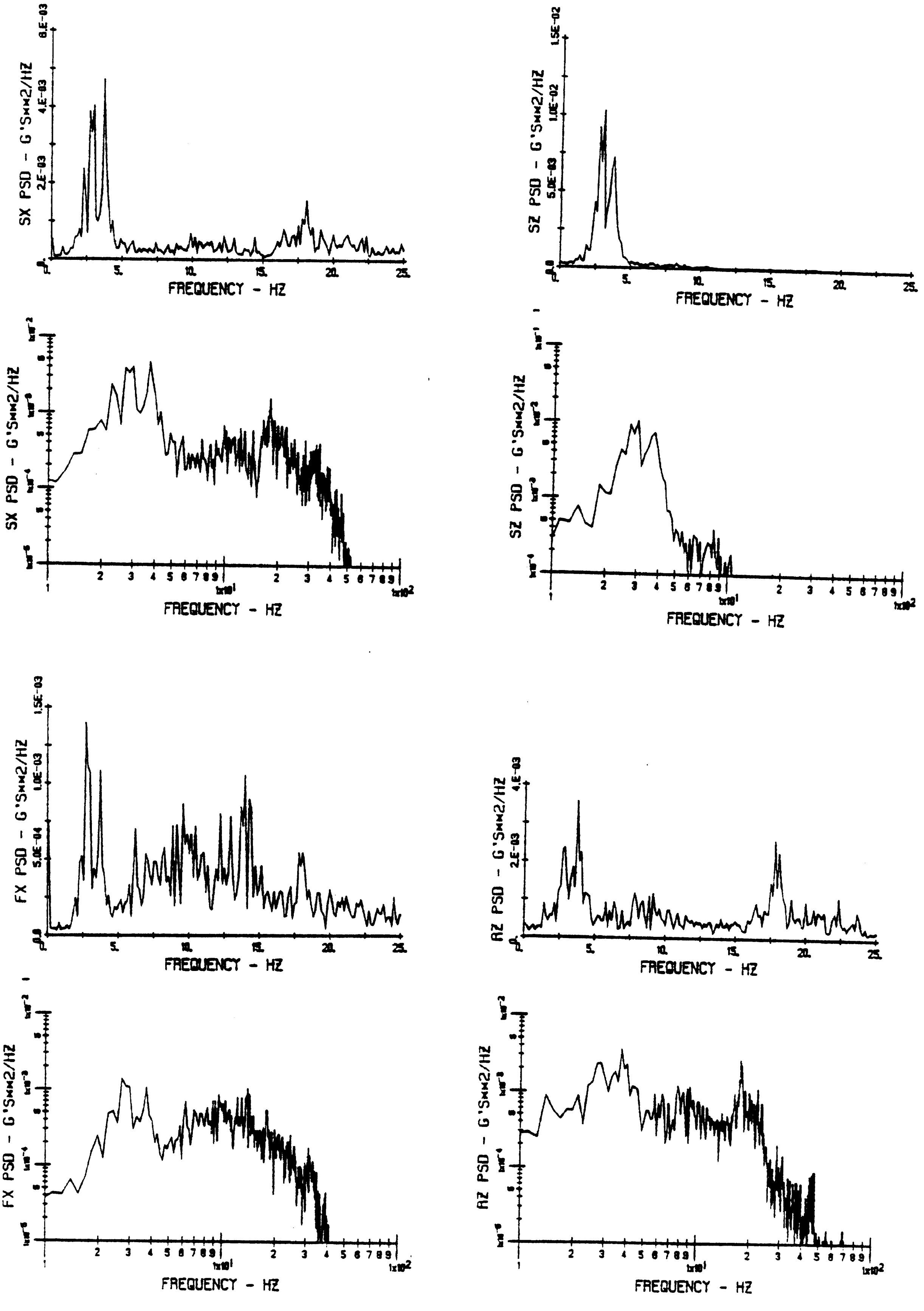


Figure B.10. Acceleration PSDs for loaded truck on Site #5 at 45 mph. (Rough bituminous road)

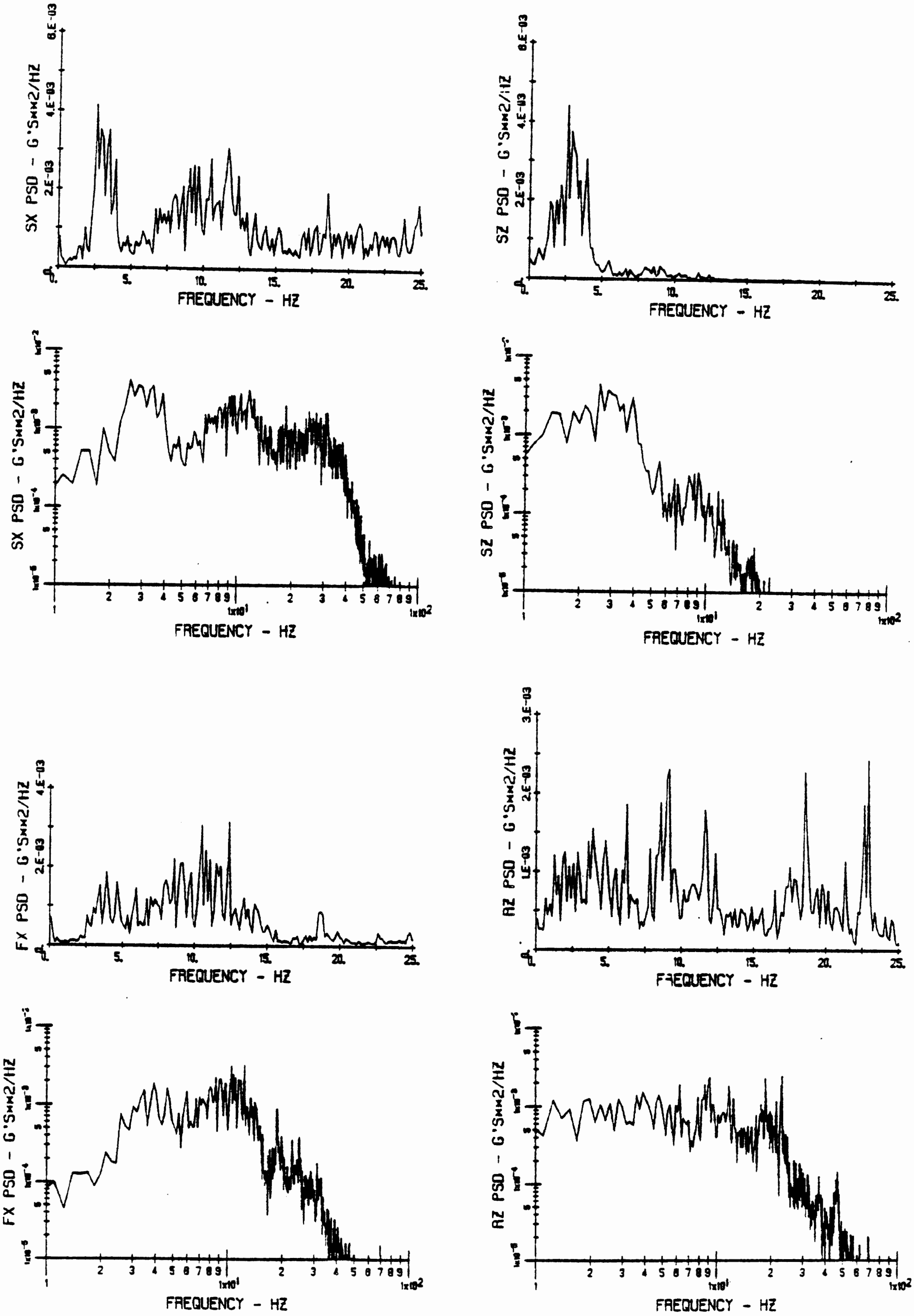


Figure B.11. Acceleration PSDs for unloaded truck on Site #5 at 45 mph. (Rough bituminous road)

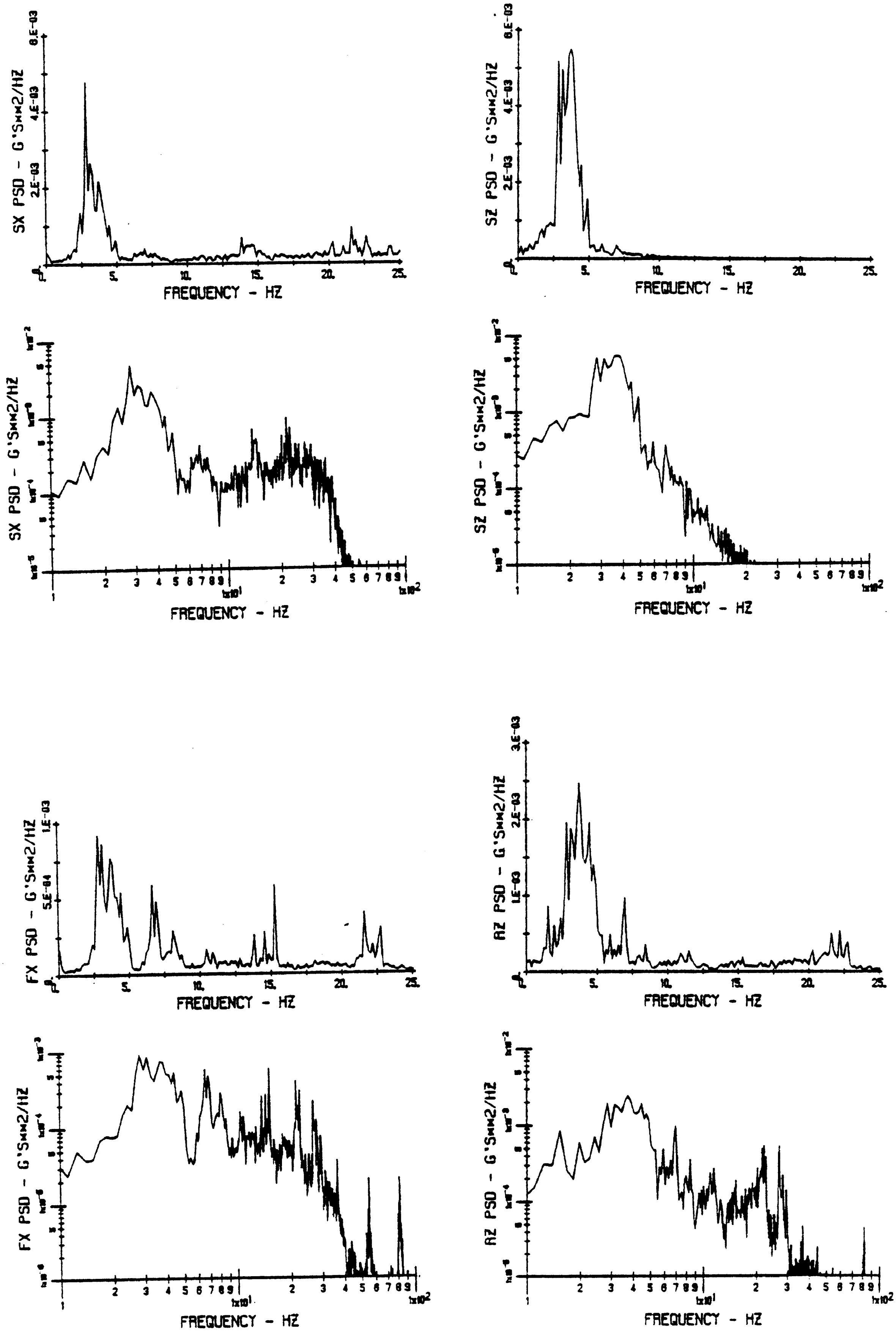


Figure B.12. Acceleration PSDs for loaded truck on Site #6 at 55 mph. (Smooth PCC road)

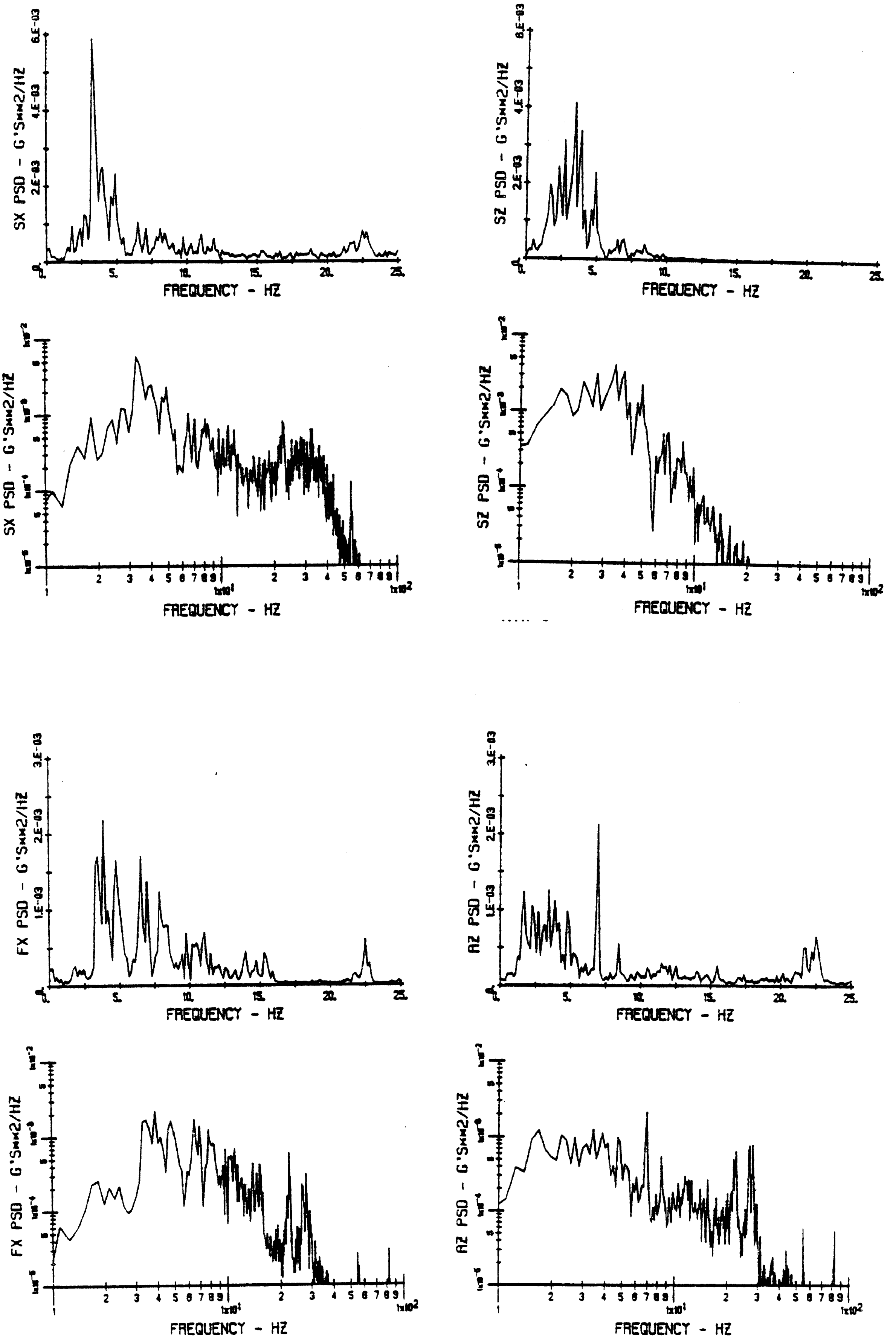


Figure B.13. Acceleration PSDs for unloaded truck on Site #6 at 55 mph. (Smooth PCC road)

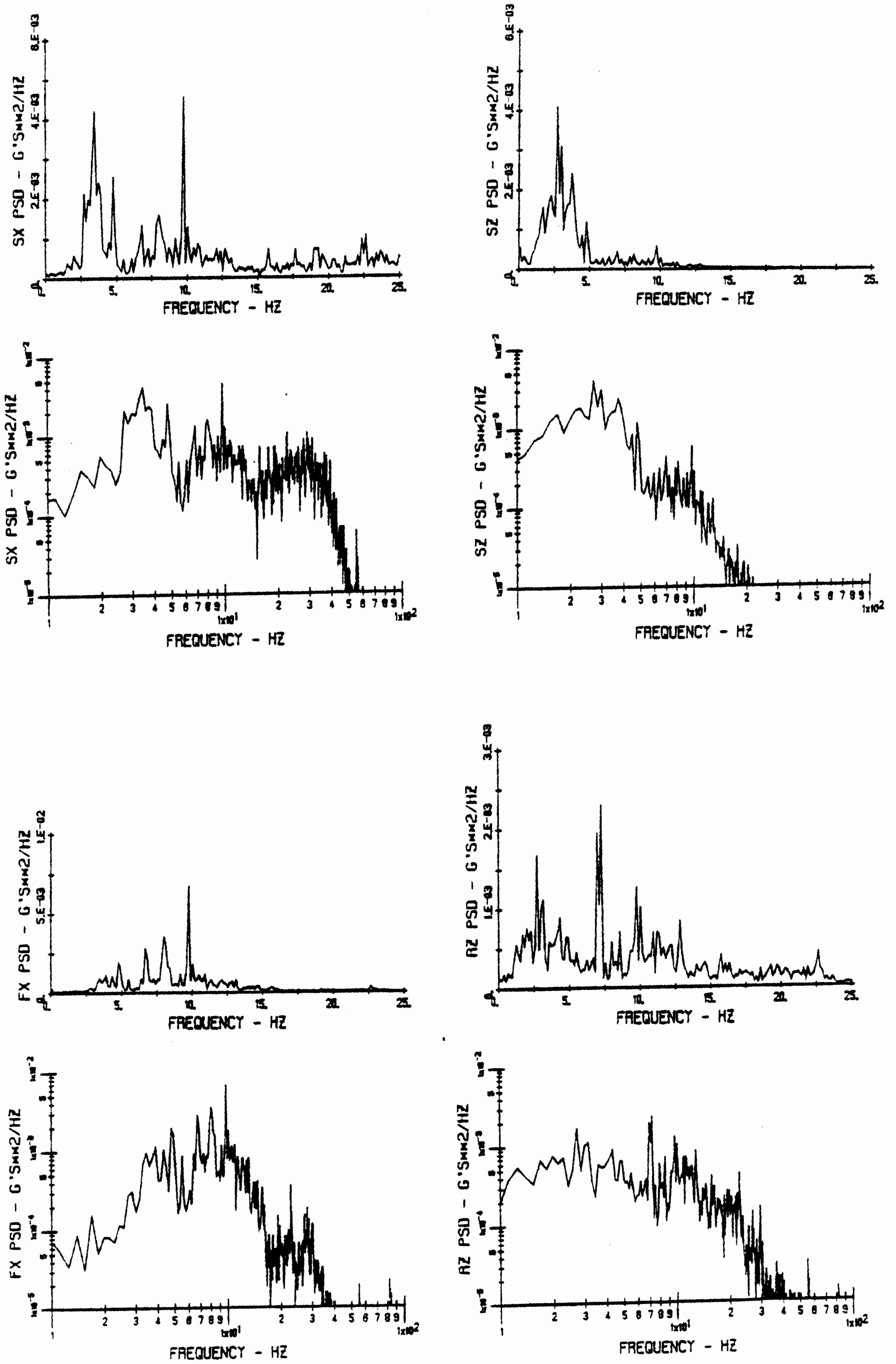


Figure B.14. Acceleration PSDs for unloaded truck on Site #8 at 55 mph. (Moderate PCC road)

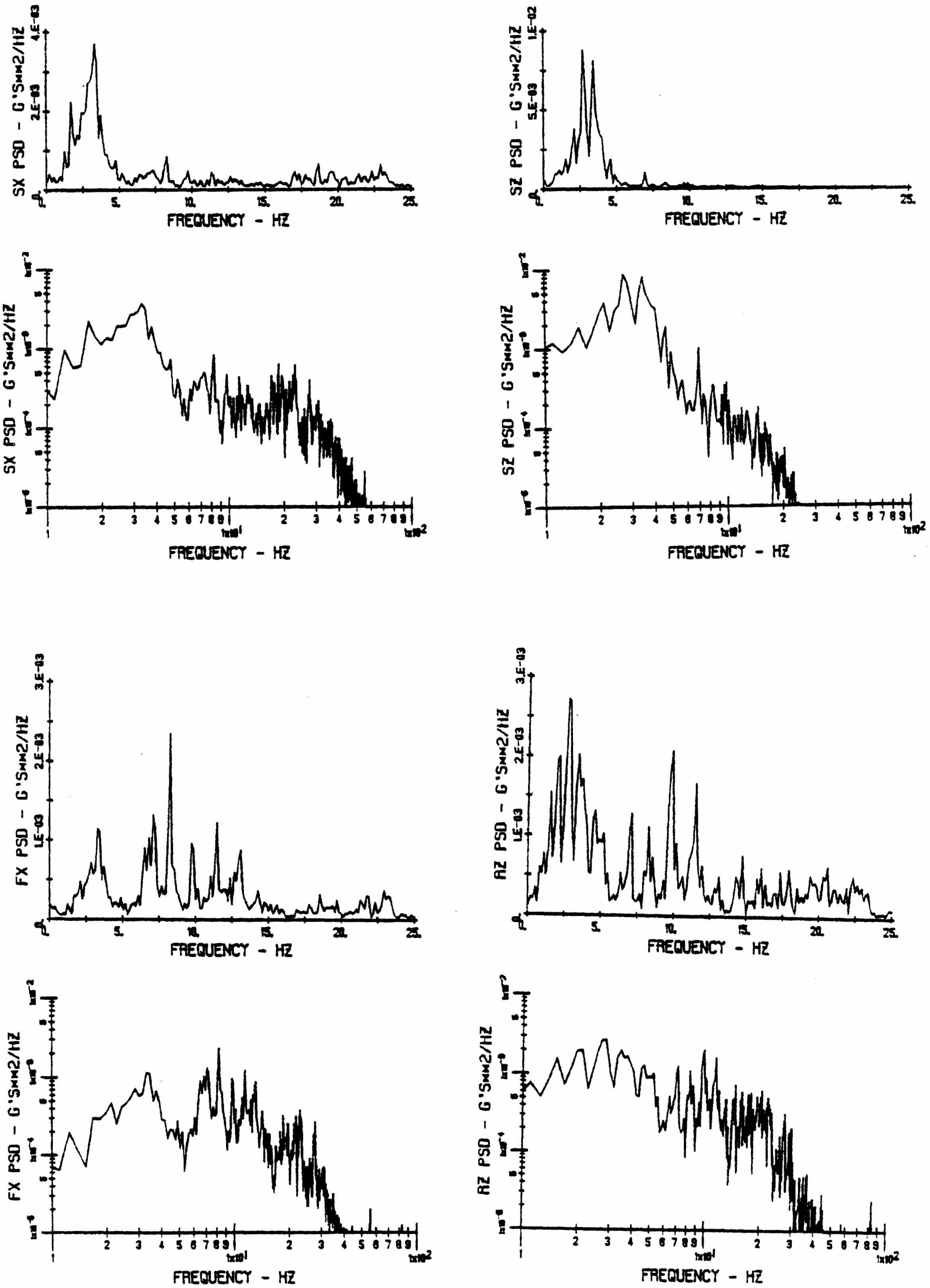


Figure B.15. Acceleration PSDs for loaded truck on Site #10 at 55 mph. (Rough PCC road)

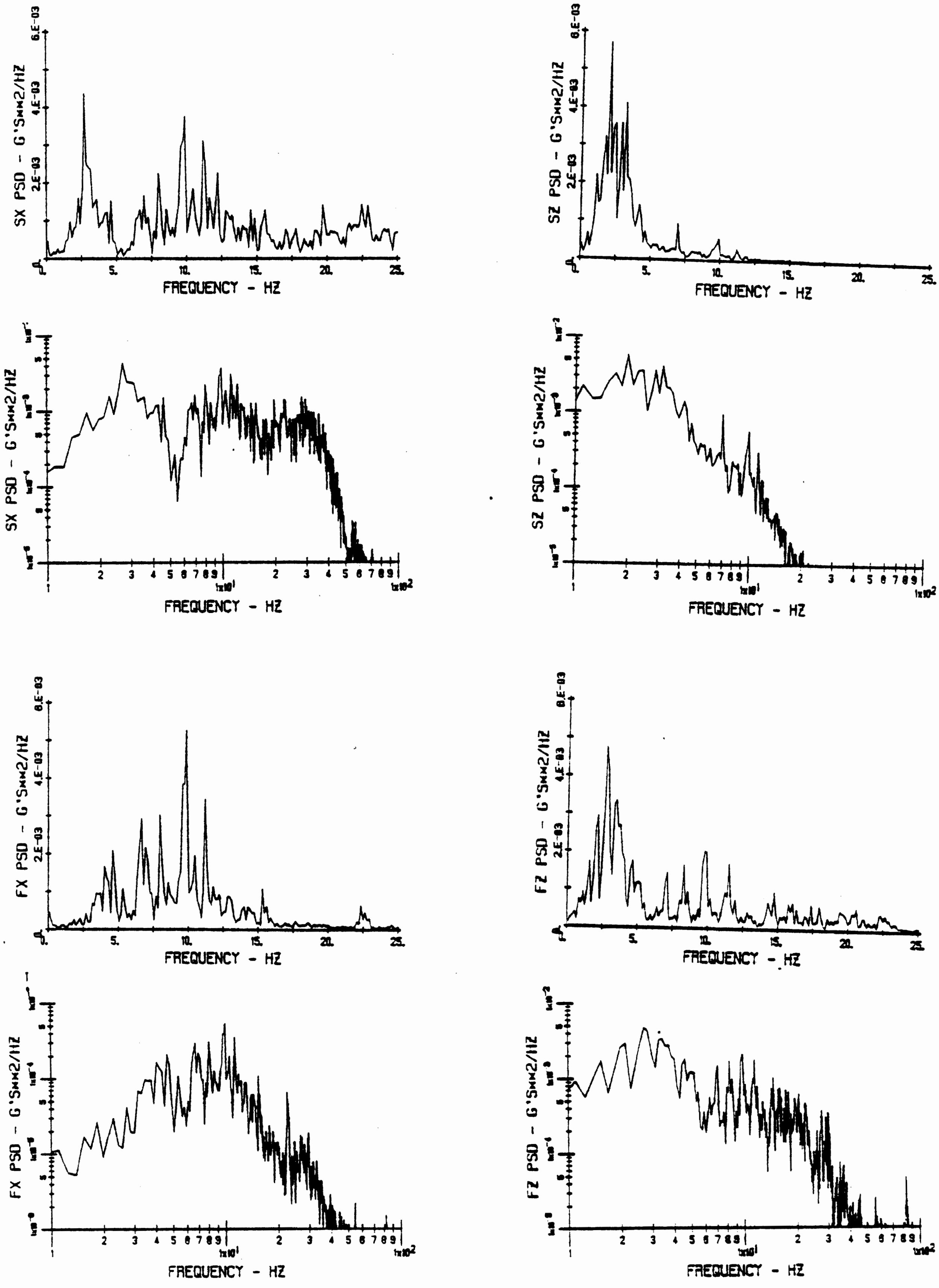


Figure B.16. Acceleration PSDs for unloaded truck on Site #10 at 55 mph. (Rough PCC road) rougher roads, and onthe PCC-type roads (as expected from the many spectral peaks displayed in the PCC roads themselves in Figure B.4). Generally, the unloaded truck shows more response at lower frequencies (less than 15 Hz) and similar response at higher frequencies, when compared to its performance when loaded.

5) Overall, the PSDs for each variable are similar for all of the test conditions. Individual spectral peaks are not consistent between different test conditions, but the overall frequency contents of the mean-square accelerations are often similar, as are the gross shapes of the log-log plots.

Vehicle Transmissibility. Figure B.17 summarizes the relationship between road roughness as characterized by the RARV measure at simulated test speed, and the unweighted and ISO-weighted RMS vertical accelerations in the truck. Figure B.18 shows the same data for the fore/aft vibrations. Some trends shown by the figure are:

1) In most cases, increases in the roughness measurement correspond to increases in the RMS accelerations. The underlying relationship between road roughness and truck acceleration does not appear to be linear, but instead shows high sensitivity to roughness for smooth roads, and less sensitivity for rough roads.

2) The relationship between roughness and acceleration differs between the loaded and unloaded truck conditions. The vertical accelerations (FZ) deriving largely from roughness input at the front axle changes little in RMS amplitude because the front axle load is still about the same. Nevertheless, more of that energy is contained in the high frequency portion of the spectrum that is attenuated by the seat's vertical isolation system such that the overall seat vertical vibrations (SZ) are somewhat reduced in the unloaded condition. The same is not true of the fore/aft direction which is heavily influenced by roughness input at the unloaded rear axle. In

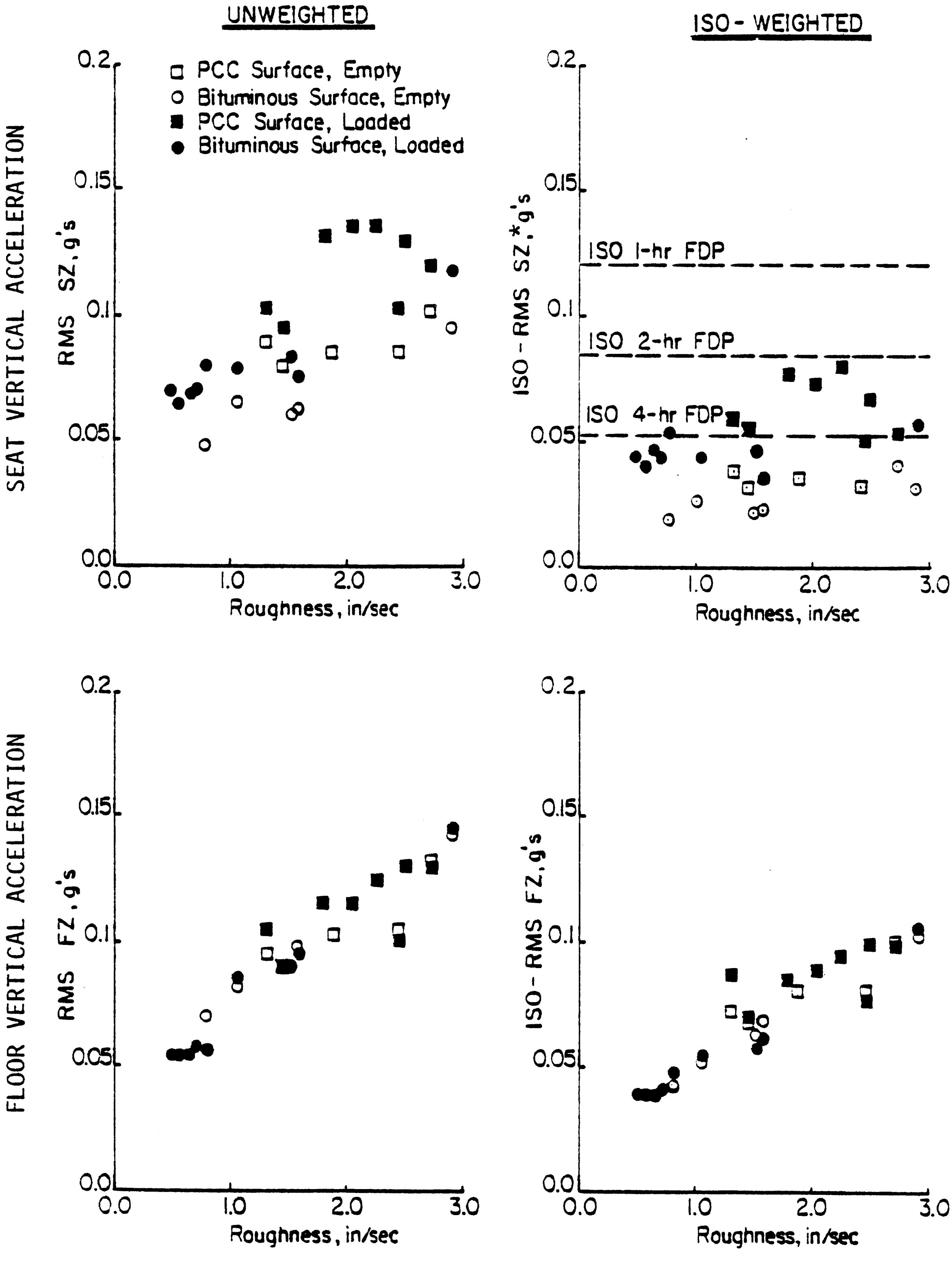


Figure B.17. RMS vertical vibration levels of a truck as a function of road roughness.

*Based on a one-third octave bandwidth

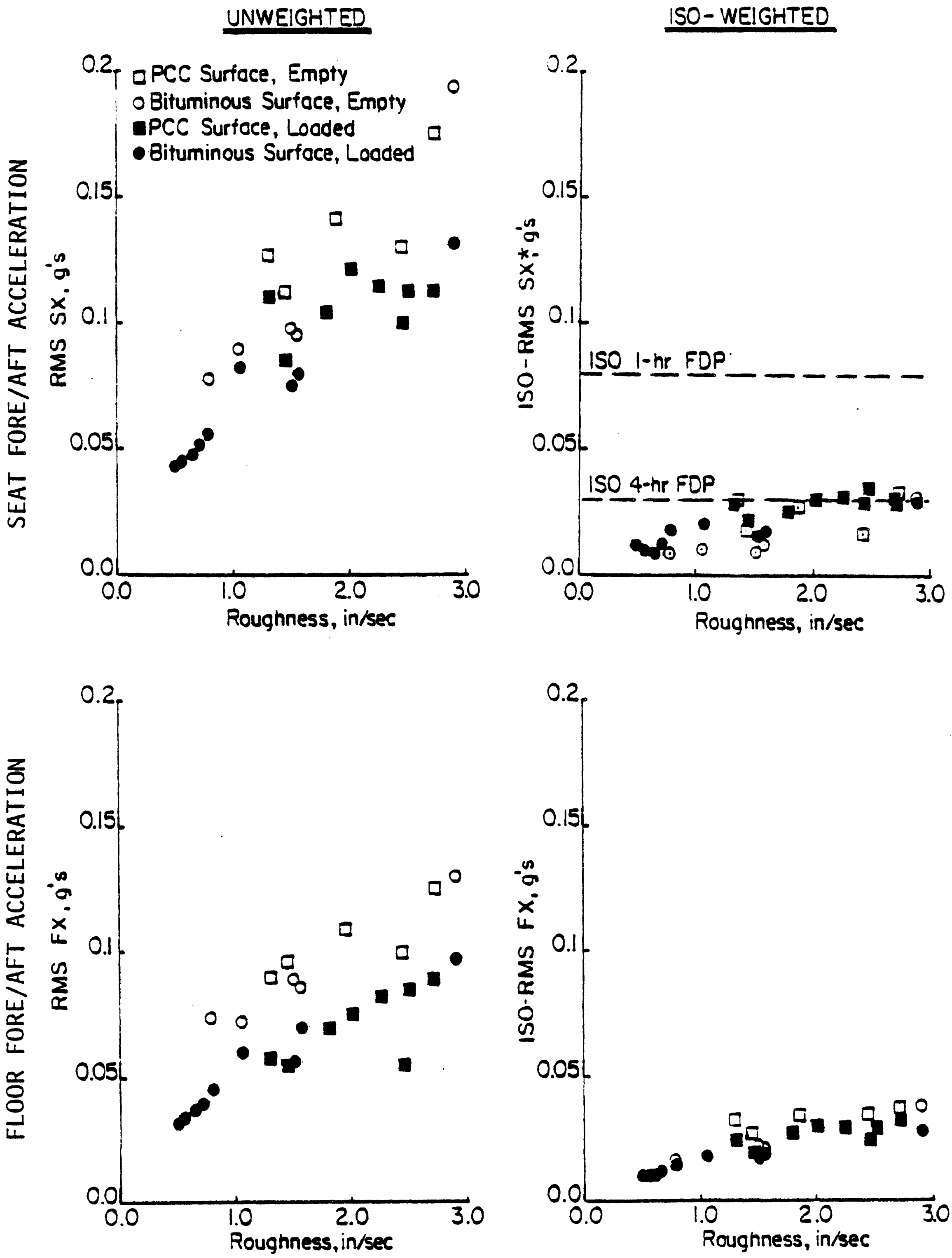


Figure B.18. RMS fore/aft vibration levels of a truck as a function of road roughness.

*Based on a one-third octave bandwidth

general, much larger RMS fore/aft accelerations (FX) occur, with significant content at the higher frequencies. Inasmuch as this seat did not have fore/aft isolation, much of the vibration gets through to the seat (SX). Applying the ISO weighting, however, suppresses the high frequency portion so that the ISO-weighted RMS values of SX are less sensitive to the vehicle's load condition.

3) The floor vertical vibrations are the most directly influenced by road roughness (that is, the plot of RMS versus RARV shows the least scatter), while the seat vertical vibrations are the least influenced (most scatter).

The mechanisms behind these trends can be seen, to some extent, by studying plots of the transmissibility ratio, expressed by:

$$\text{Gain} = \frac{\text{truck acceleration PSD}}{\text{road acceleration PSD}}$$

Figures B.19-B.26 show these ratios, which approximate the transmissibility gains for the truck for a variety of conditions. Figure B.27 shows the exact transmissibility of the quarter-car simulation used to provide the roughness measures from profile measurements expressed as a gain function appropriate to the measurement process. The gain is seen to be qualitatively similar to the curves shown in Figures B.19-B.26, so that it is not surprising to see the quarter-car roughness measure closely matched to the cab floor vertical response. This explains the good agreement between RARV and RZ (and FZ—a relationship apparent from the tables, but not plotted). On the other hand, the approximate gain for SZ rolls off sharply above 4 Hz; hence, the RARV includes high-frequency content lacking in the RMS SZ statistic, explaining the high amount of scatter shown in Figure B.17.

B.5 Conclusions

Based on the results of the experiments reported here, it has been demonstrated that there is a rather direct relationship between road roughness level as would be measured by a highway agency's roadmeter and

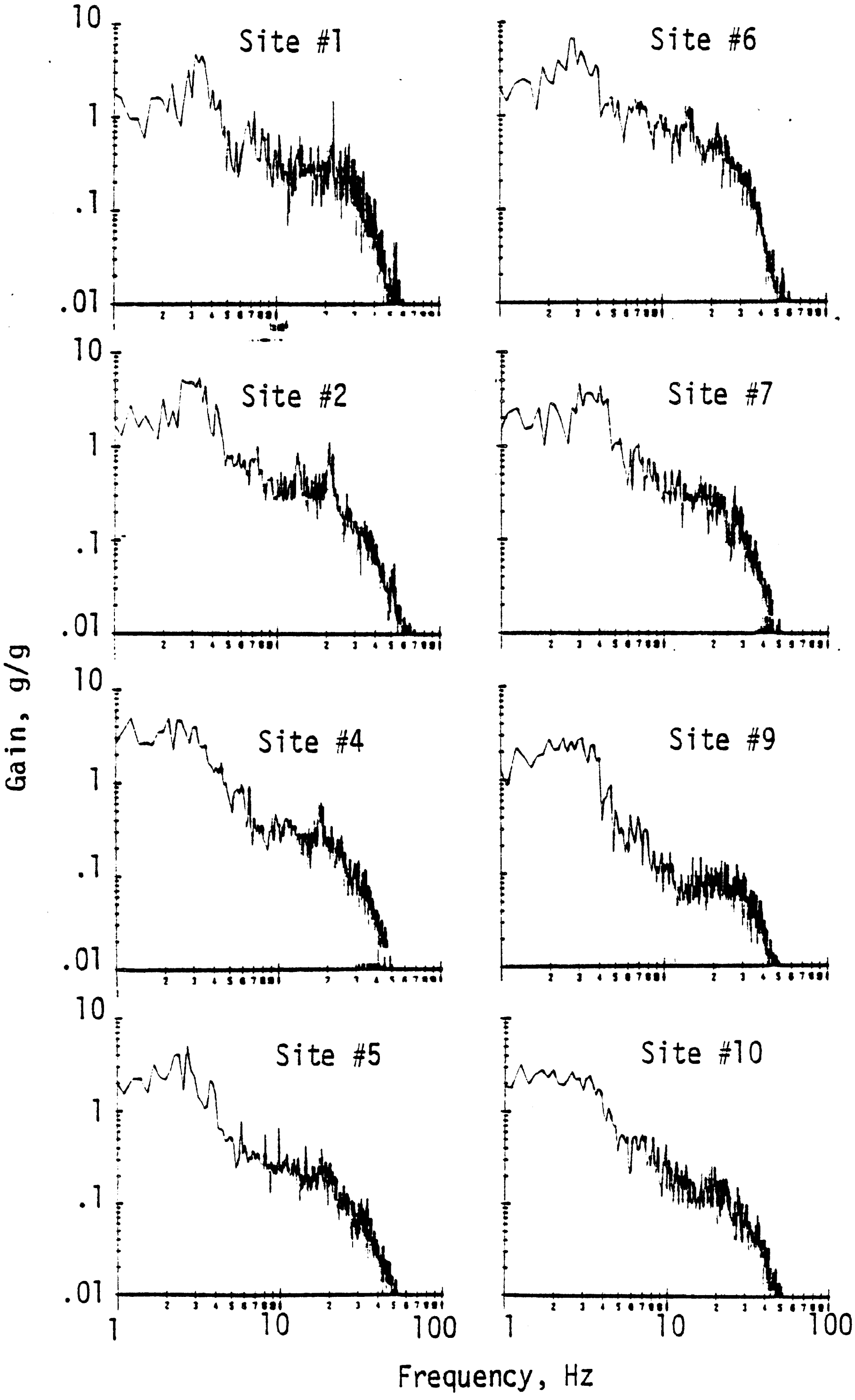


Figure B.19. Approximate gains: SX/road acceleration for loaded truck.

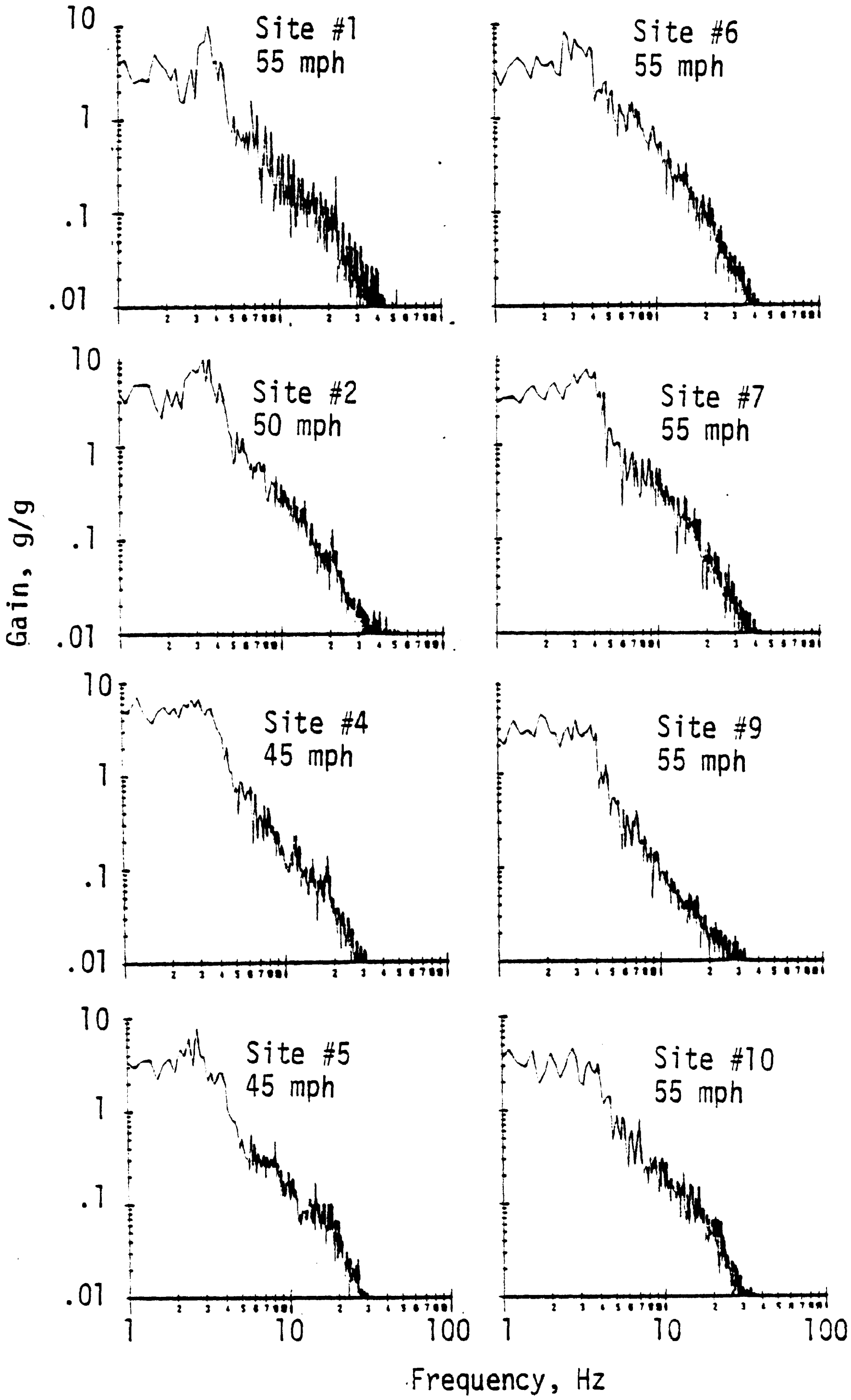


Figure B.20. Approximate gains: SZ/road acceleration for loaded truck.

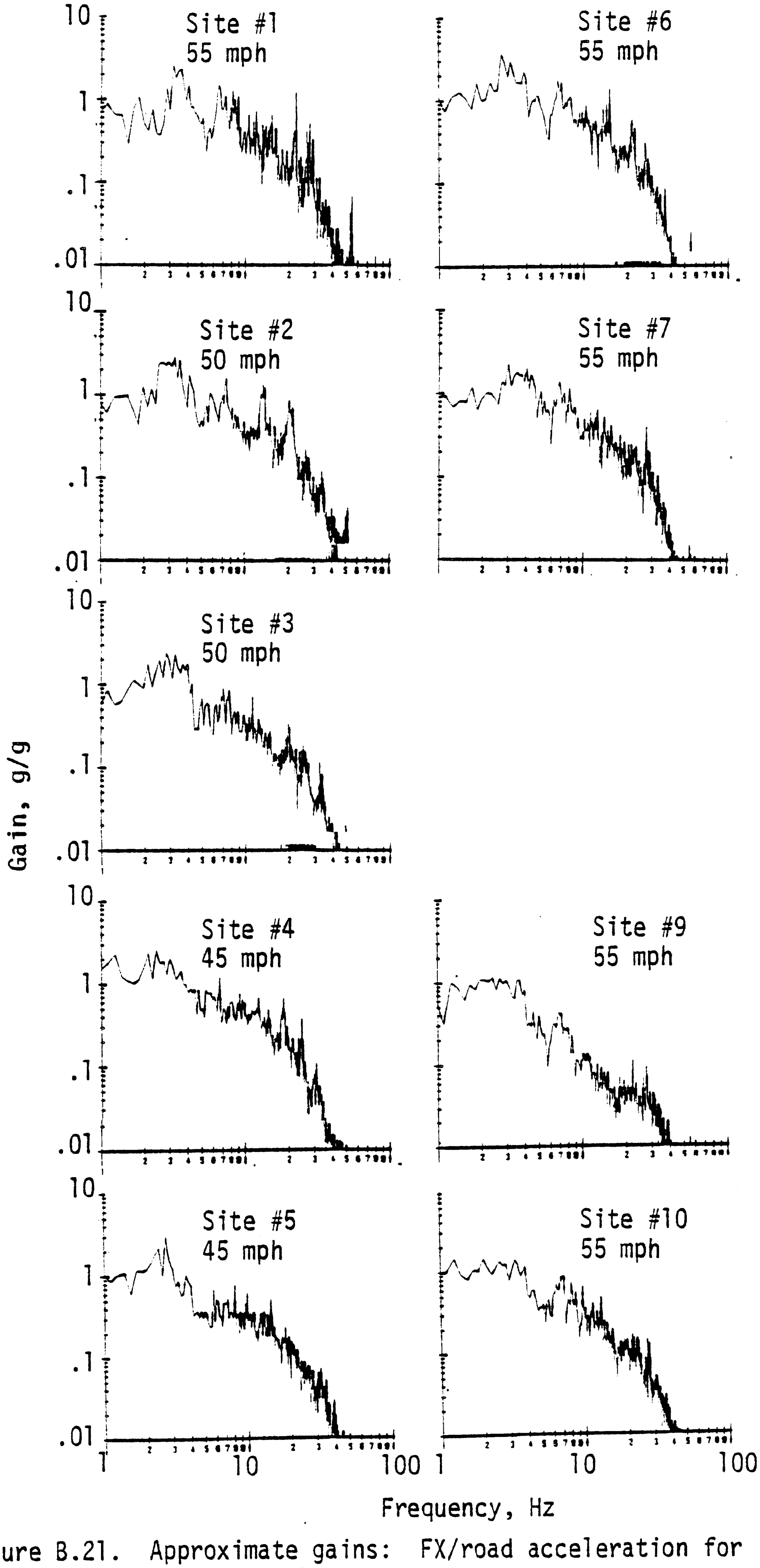


Figure B.21. Approximate gains: FX/road acceleration for loaded truck.

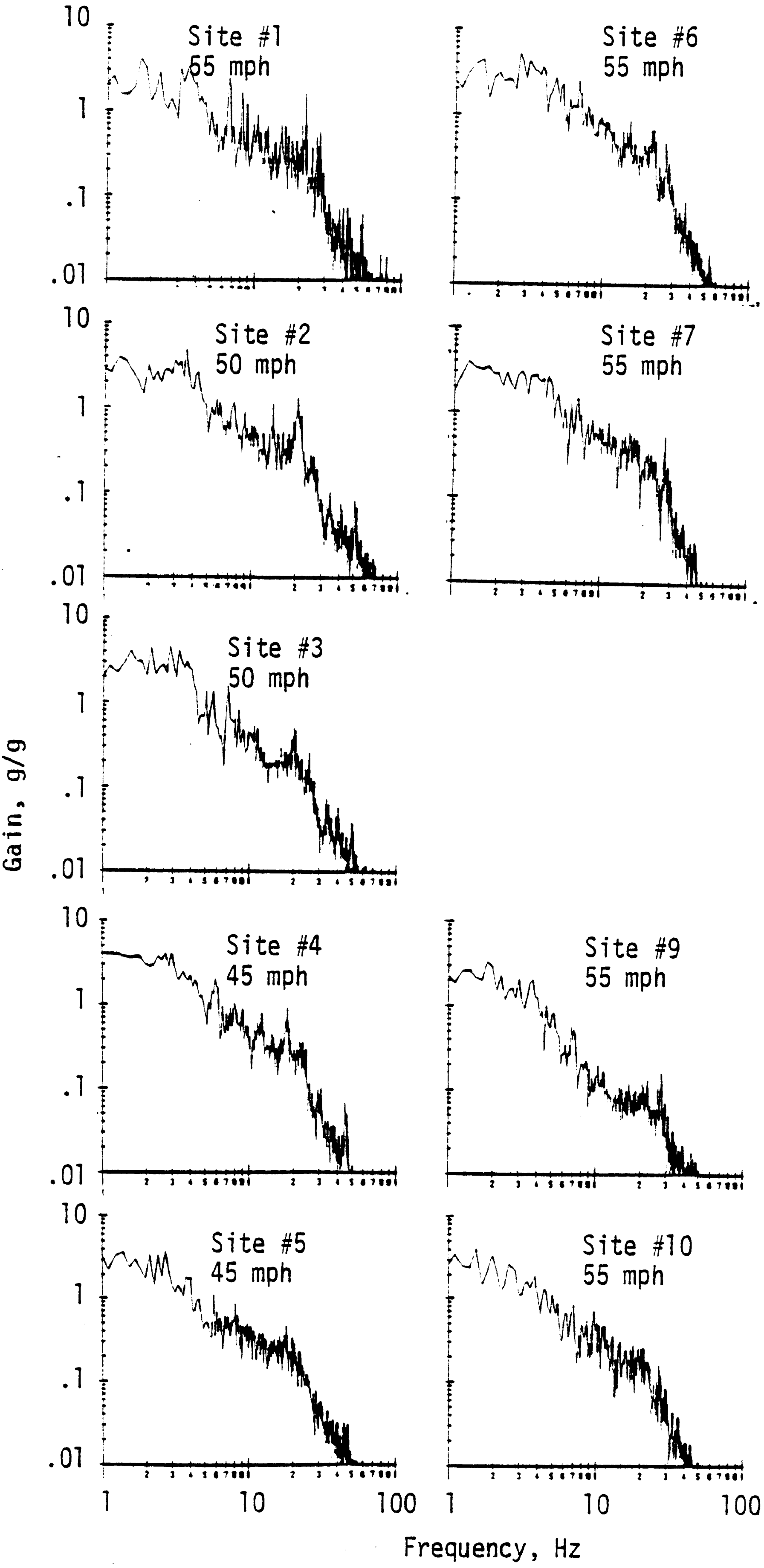


Figure B.22. Approximate gains: RZ/road acceleration for loaded truck.

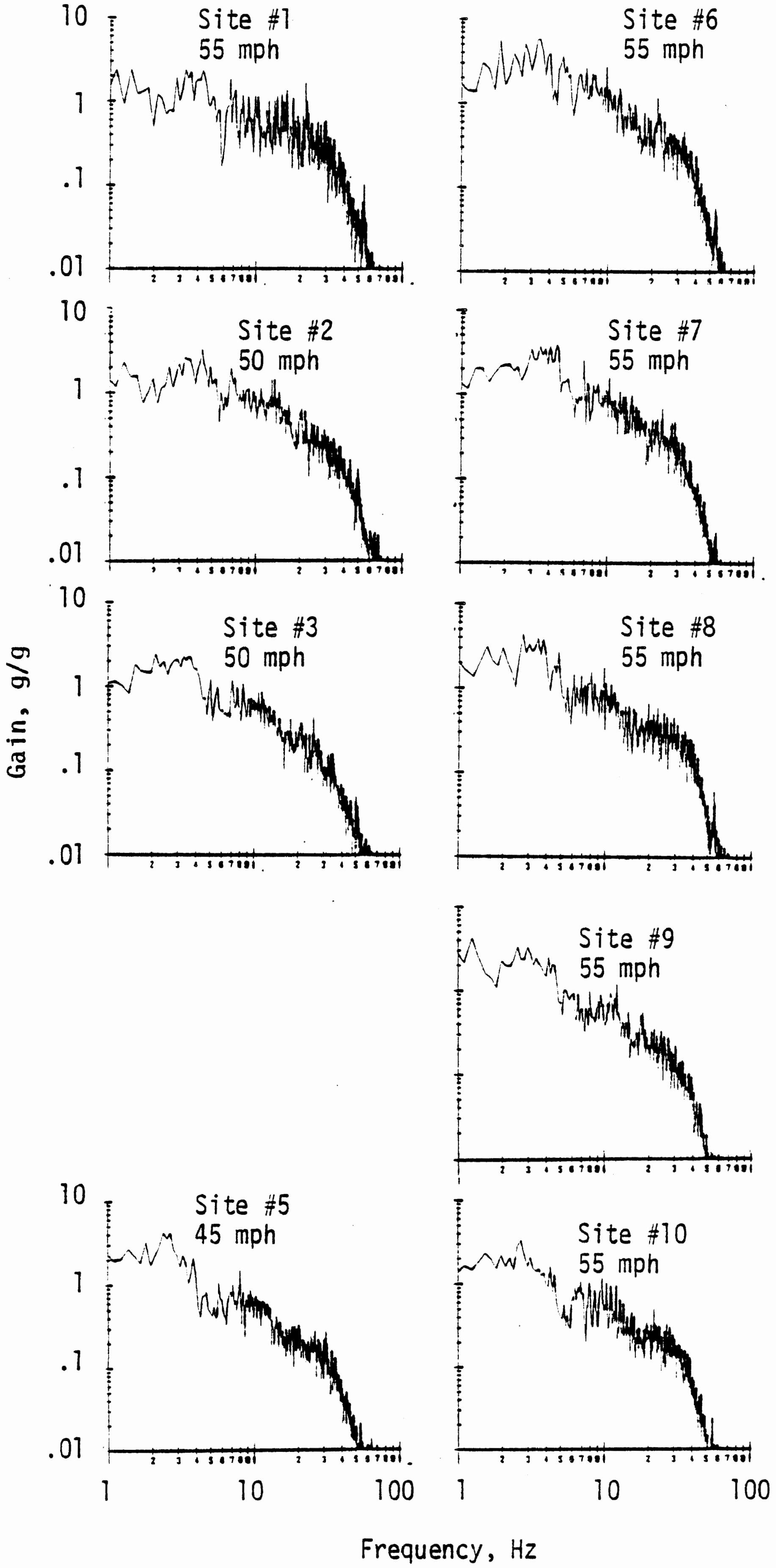


Figure B.23. Approximate gains: SX/road acceleration for unloaded truck.

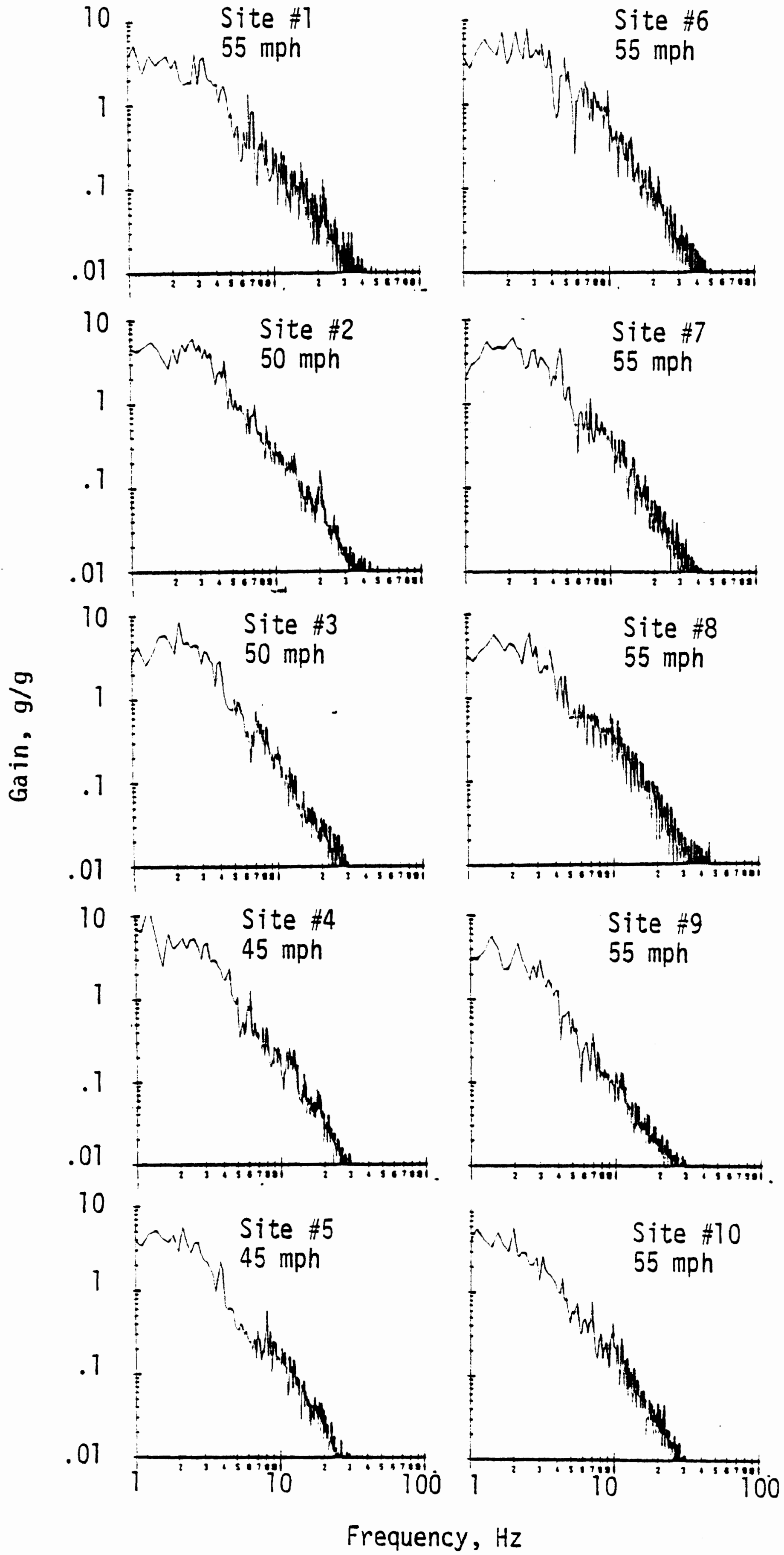


Figure B.24. Approximate gains: SZ/road acceleration for unloaded truck.

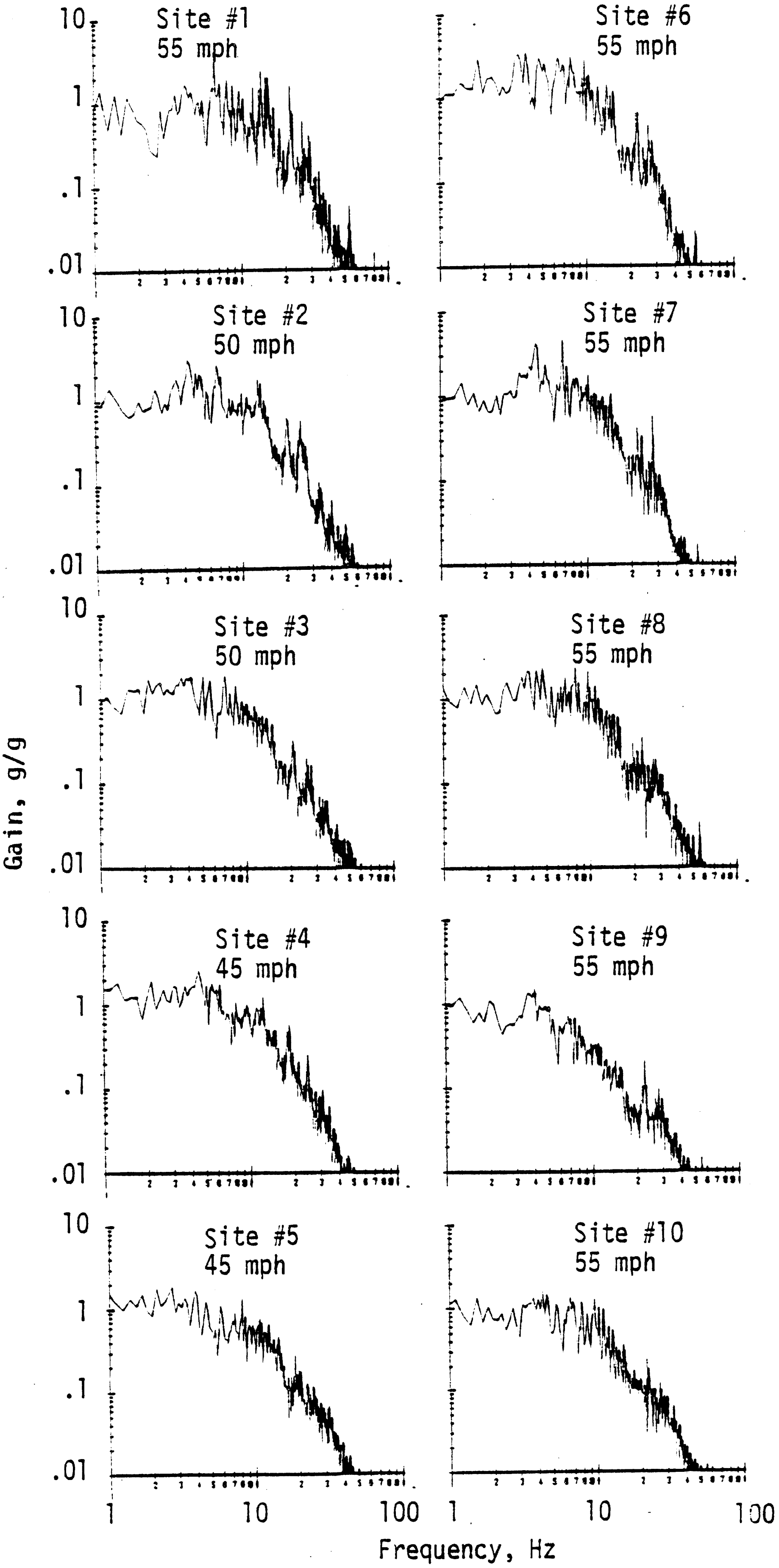


Figure B.25. Approximate gains: FX/road acceleration for unloaded truck.

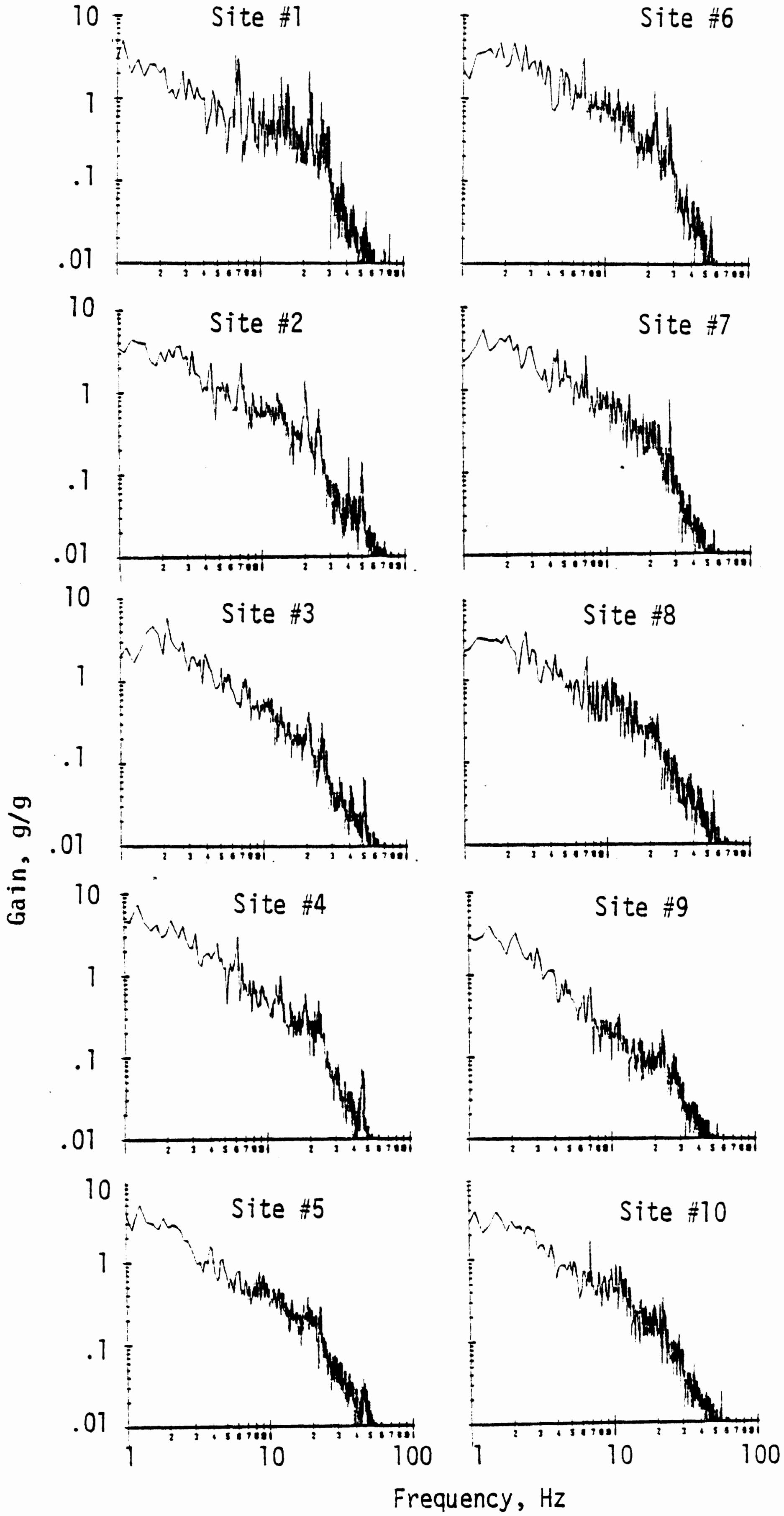


Figure B.26. Approximate gains: RZ/road acceleration for unloaded truck.

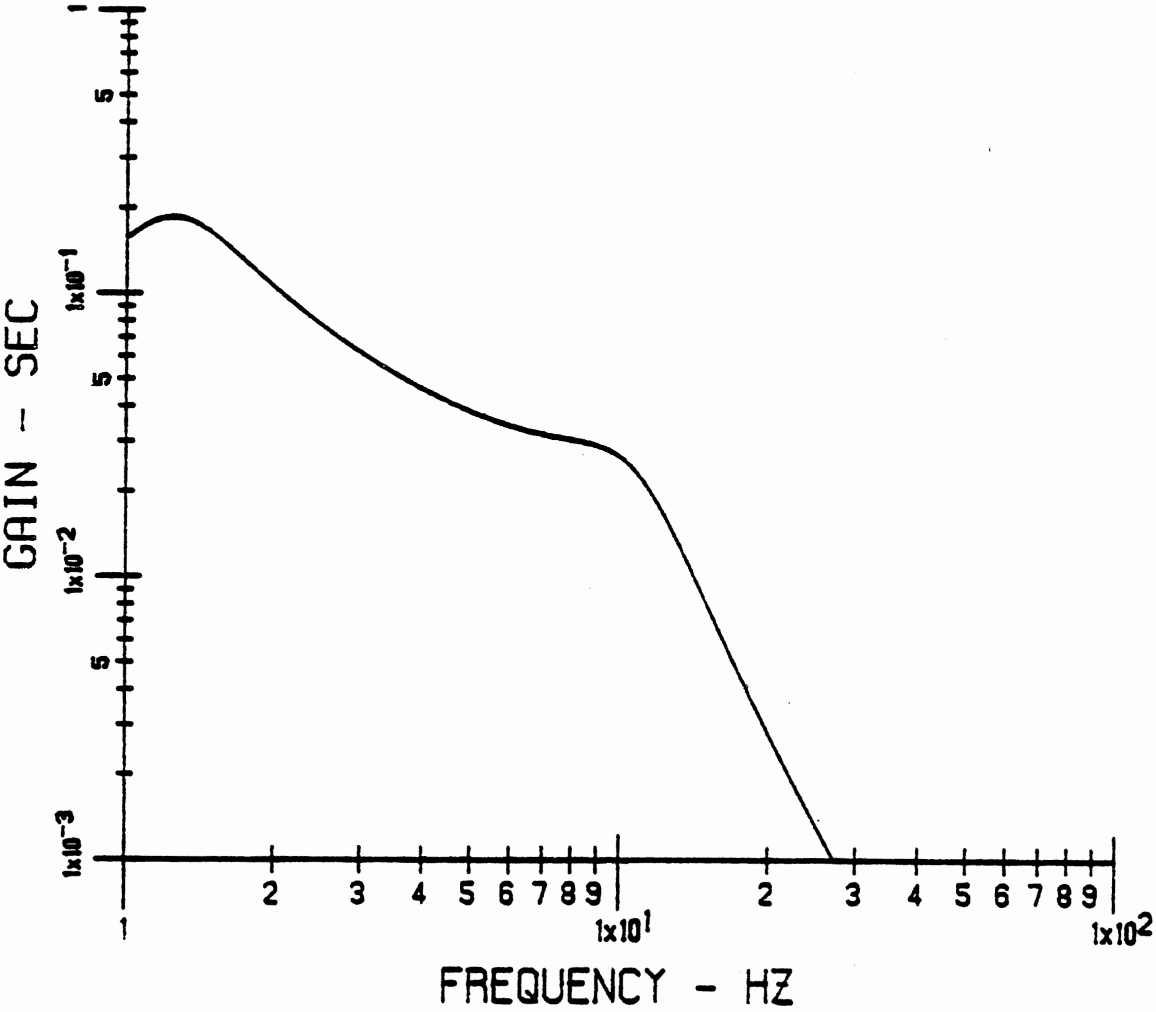


Figure B.27. Response of quarter-car simulation roughness numeric: (Velocity Out)/(Acceleration In).

the vibrations induced in the chassis of a truck. Comparing the transmissibility properties of a truck over a range of surface types indicates a fairly consistent behavior that is qualitatively similar to the roughness measurement process.

The result, as was summarily shown in Figures B.17 and B.18, is that

1) The chassis RMS vertical vibrations (as characterized by RZ), whether loaded or unloaded, are very directly proportional to the road roughness level, quantified by the RARV.

2) The chassis RMS fore/aft vibrations (FX) and the seat RMS fore/aft vibrations (SX) are closely linked to roughness level; but, being a consequence of pitch dynamics, are more variable with load and speed.

3) The truck seat RMS vertical vibrations (SZ), because of the seat isolation system, are less precisely related to road roughness level. Nevertheless, the seat vibration levels tend to increase with roughness and are of the same quantitative range as the chassis vertical vibrations.

For the vehicle tested, road roughness evaluated at the operating speed was a primary determinant of the driver vibration exposure. For this vehicle, the ISO-weighted acceleration levels to which the driver was exposed exceeded the four-hour Fatigue Decreased Proficiency (FDP) boundary under a number of different conditions. In general, the most severe vibrations are observed as the road roughness increases to the level of 1.6 to 2.0 in/sec RARV (nominally equivalent to PSI values of 3.0 and 2.5, respectively). At that point, the loaded vehicle produces seat vertical vibration levels approaching the two-hour FDP boundary on PCC roads.

Though the exact levels of vibration, as judged against the ISO criteria, are clearly a function of the vehicle, load condition, speed, and road surface type (bituminous or PCC), the general trend is evident that truck vibration levels will necessarily increase with road roughness condition. Using the subject truck as an example, it may be projected that allowing the condition of roads to deteriorate below the marginal level of 3.0 PSI will result in driver exposure to vibration levels equivalent to the two-hour ISO FDP limit.