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

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16. Abstract

Vibration exposure to drivers of trucks and tractor-trailers has often been implicated as a negative influence on highway safety. This document examines the state-of-knowledge in the links between the truck ride vibration environment and the potential for accident causation as it may affect accident frequency. The truck ride vibration environment is characterized by the dominant excitation sources and truck response modes, as background to understand the vibration amplitudes and spectra reported for typical trucks as available from the literature. From this knowledge, the effects of vibration on man are examined to discover the physical (biodynamic) response appropriate to the truck environment and the associated physiological, psychological, and pathological effects that may be precipitated. The performance changes of likely significance to the truck driving task are identified, and translated into scenarios of six possible ways in which vibrations may impact on accident causation. Thence, the truck accident experiences as known from the accident reporting systems of FARS, BMCS, and four states are examined to assess the degree to which accident involvement can be related to these effects.

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This document summarizes the state-of-knowledge with respect to the relationship between the ride vibration exposure of truck drivers and highway safety. Because of the broad areas and disciplines involved, many people on the HSRI staff contributed to its writing. Professor Leonard Segel authored the introductory section and served as the editor. Dr. Thomas D. Gillespie authored Section 2 on the truck ride vibration environment. Dr. Larry Schneider prepared the third 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 final section which examines the evidence to relate vibration exposure to accident frequency was prepared by Dr. Ken Campbell with assistance from Dr. Oliver Carsten.

1.0 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.

Recently, the Federal Highway Administration (FHWA) initiated a long-term research program to determine whether ride vibrations in commercial vehicles impact on motor carrier safety, inasmuch as federal responsibility for increasing highway safety is mandated under public law. At present, this effort has been suspended, pending a review of the facts which speak to the connection between truck ride quality and highway safety. This document has been prepared to facilitate that review.

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, primary emphasis is given to issues related to highway safety. In that context, driver health is of interest only insofar 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?" and

2. "Are there ongoing developments in trucking and highway operations which give rise to a hypothesis that the process wherein a truck responds to an uneven pavement (or to internally generated disturbances) is causing reductions in the safety quality of our driver-vehicle-highway system?"

Clearcut answers cannot be provided. Other than (1) the recognition that highway pavements are possibly degrading more rapidly than repairs are being made, (2) the knowledge that considerable motivation exists for making trucking more energy efficient by increasing truck sizes and weights, and (3) the fact that trucking miles as a percentage of total vehicle miles is steadily increasing, 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 as a matter for public concern. On the other hand, evidence does exist to suggest that truck driving (as a long-term occupation) involves sufficient exposure to whole-body vibration such that some drivers eventually experience an undesirable level of morbidity.

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, three topics are addressed below. 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 actual 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 introduction.

2.0 THE TRUCK RIDE VIBRATION ENVIRONMENT

2.1 Introduction

Since the infancy of the automotive industry, the evolutionary development of the commercial truck has been driven by its own set of unique priorities. 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 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—roughness and on-board forcing.

Road Roughness refers to the vertical displacement of the road surface which occurs both longitudinally and transversely and has characteristic dimensions which excite vibrations in a traversing vehicle. 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 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 2.1. Though each road section is unique in its spectral density, all spectra show a characteristic diminishing magnitude with increasing 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 2.2 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 2.3 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

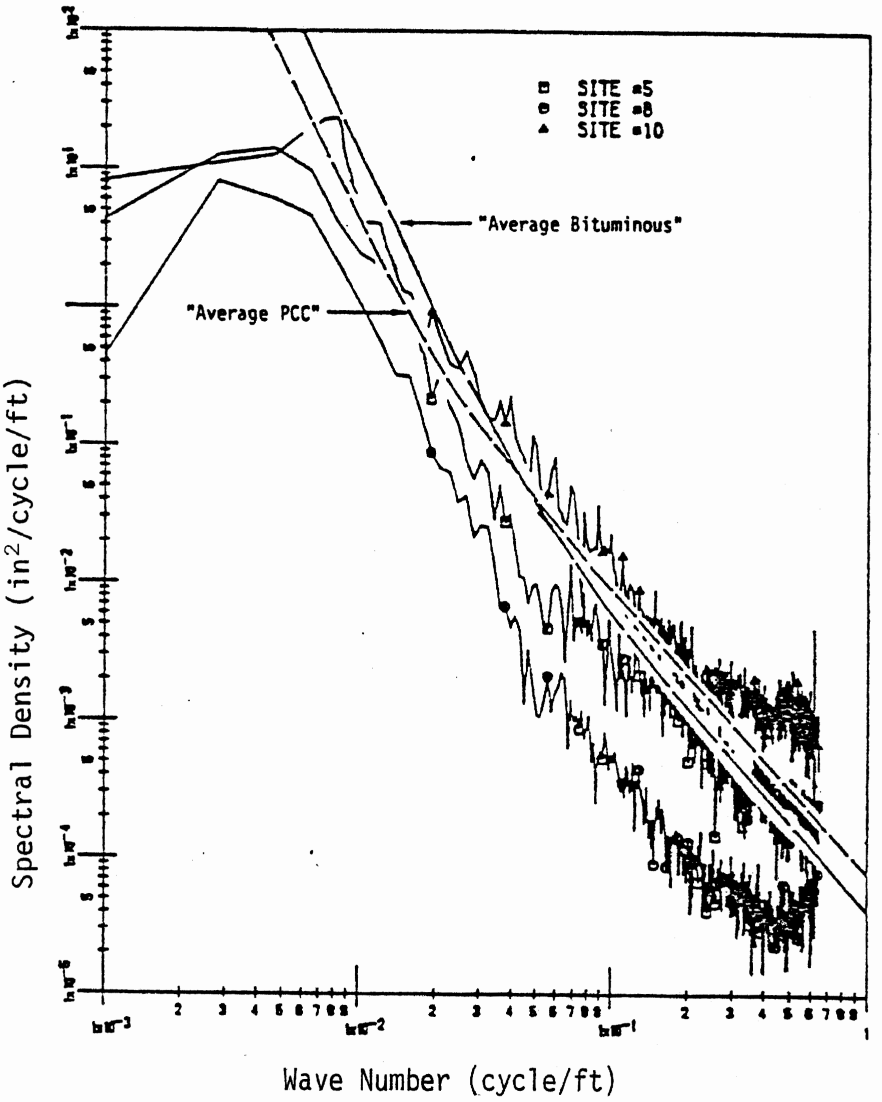


Figure 2.1. Typical spectral densities of pavement elevation (average of two tracks).

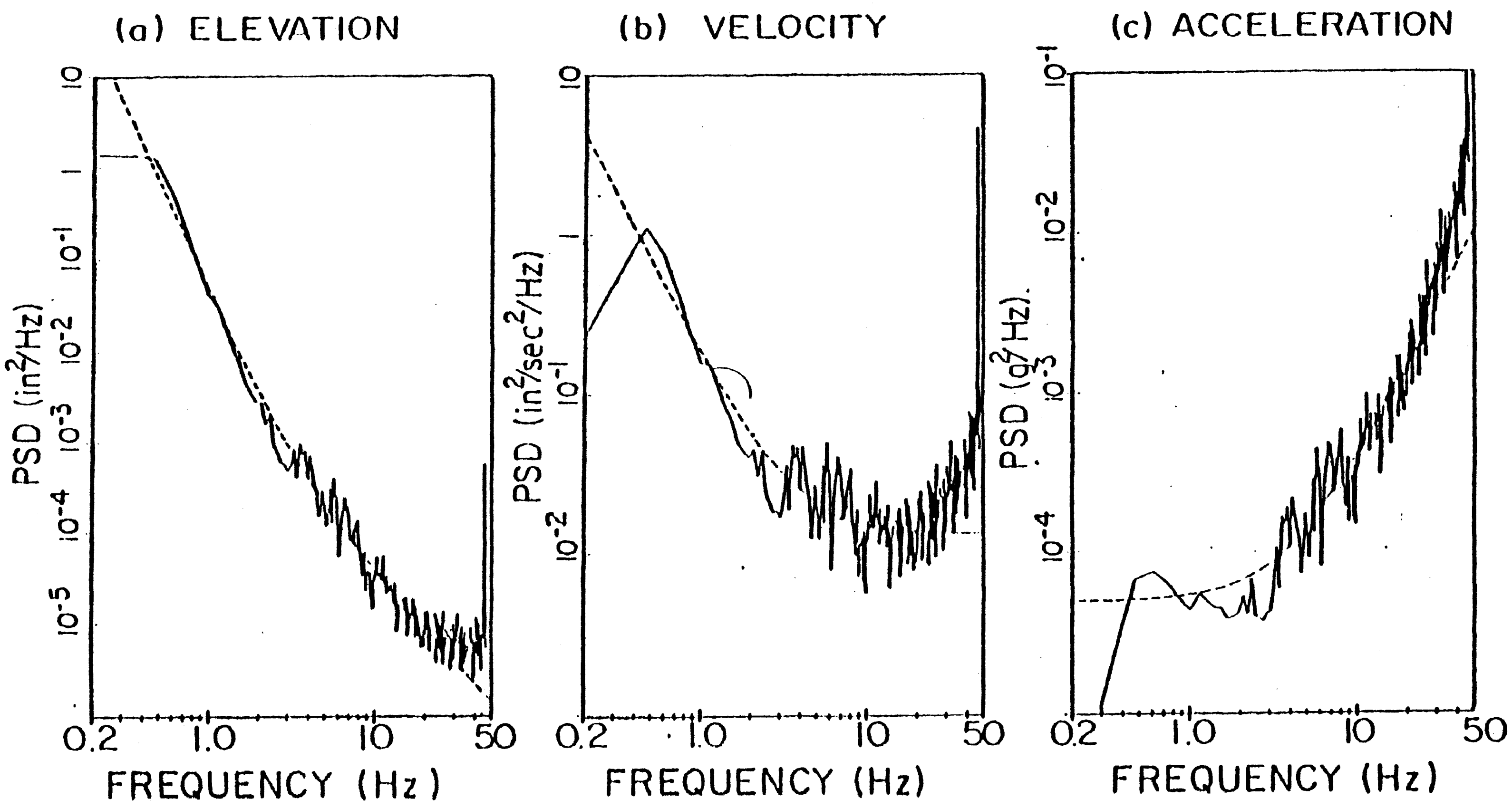


Figure 2.2. Elevation, velocity, and acceleration PSD's of the road roughness input to a vehicle traveling at 50 mph on the real and model roads

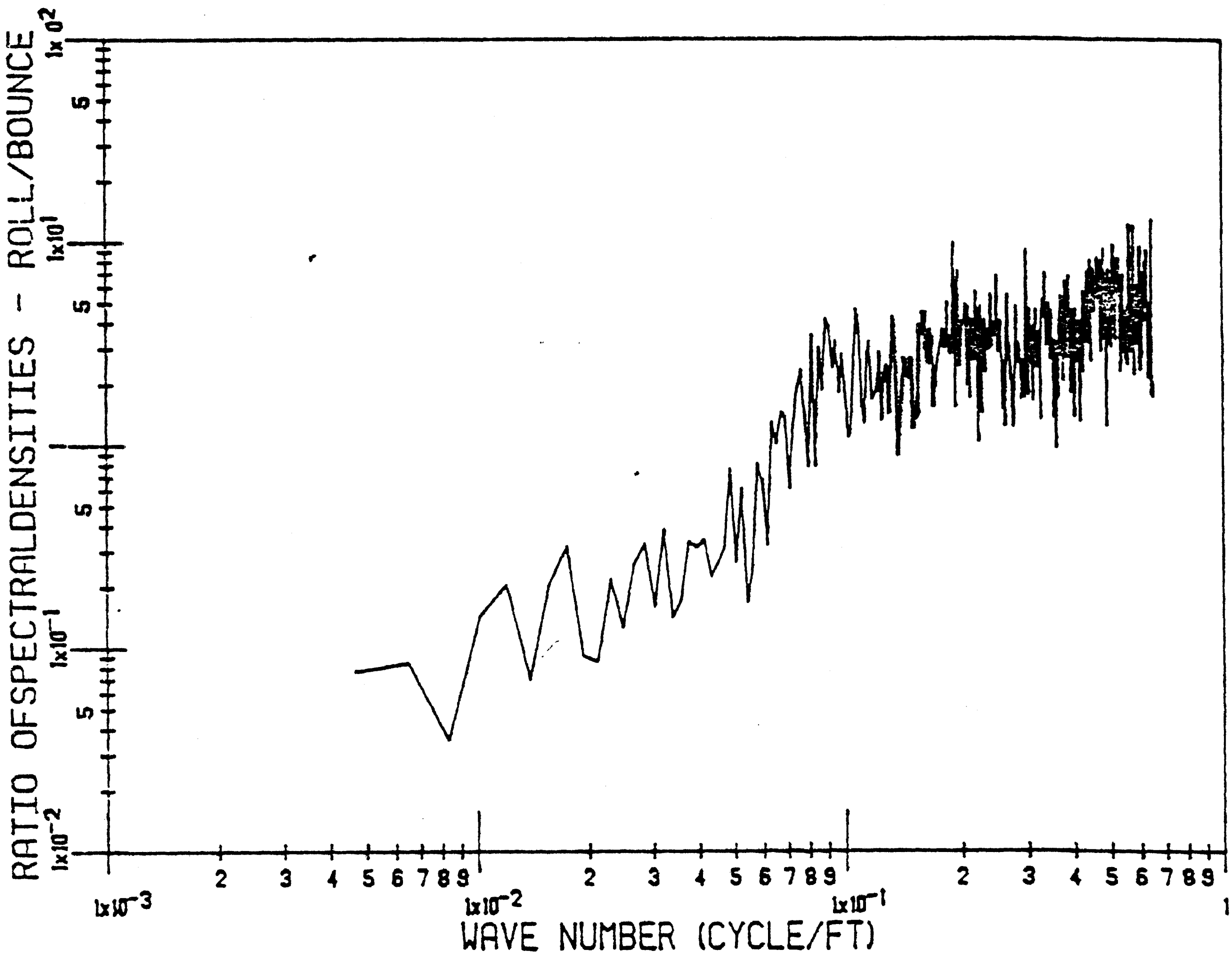


Figure 2.3. Ratio of roll to bounce spectral densities for a typical road.

corresponding to low frequency excitation of a vehicle traveling at normal speeds. In most cases, roll input only becomes comparable 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. 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 2.4. On a rougher road, the same wheel excitation causes a smaller influence, as shown in Figure 2.5, 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.

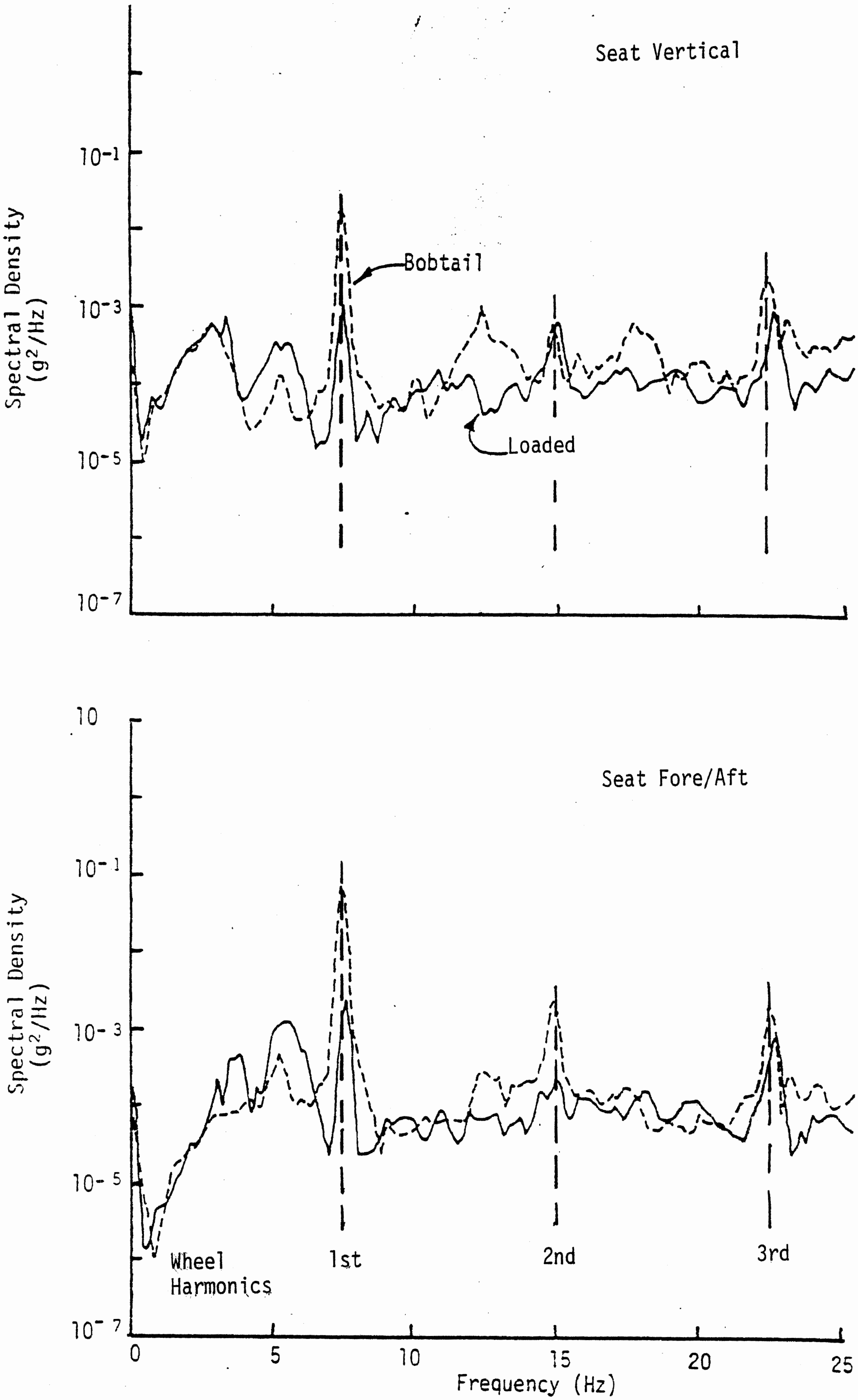


Figure 2.4. PSD's of bobtail vs. loaded combination - COE tractor, 55 mph, on a smooth road.

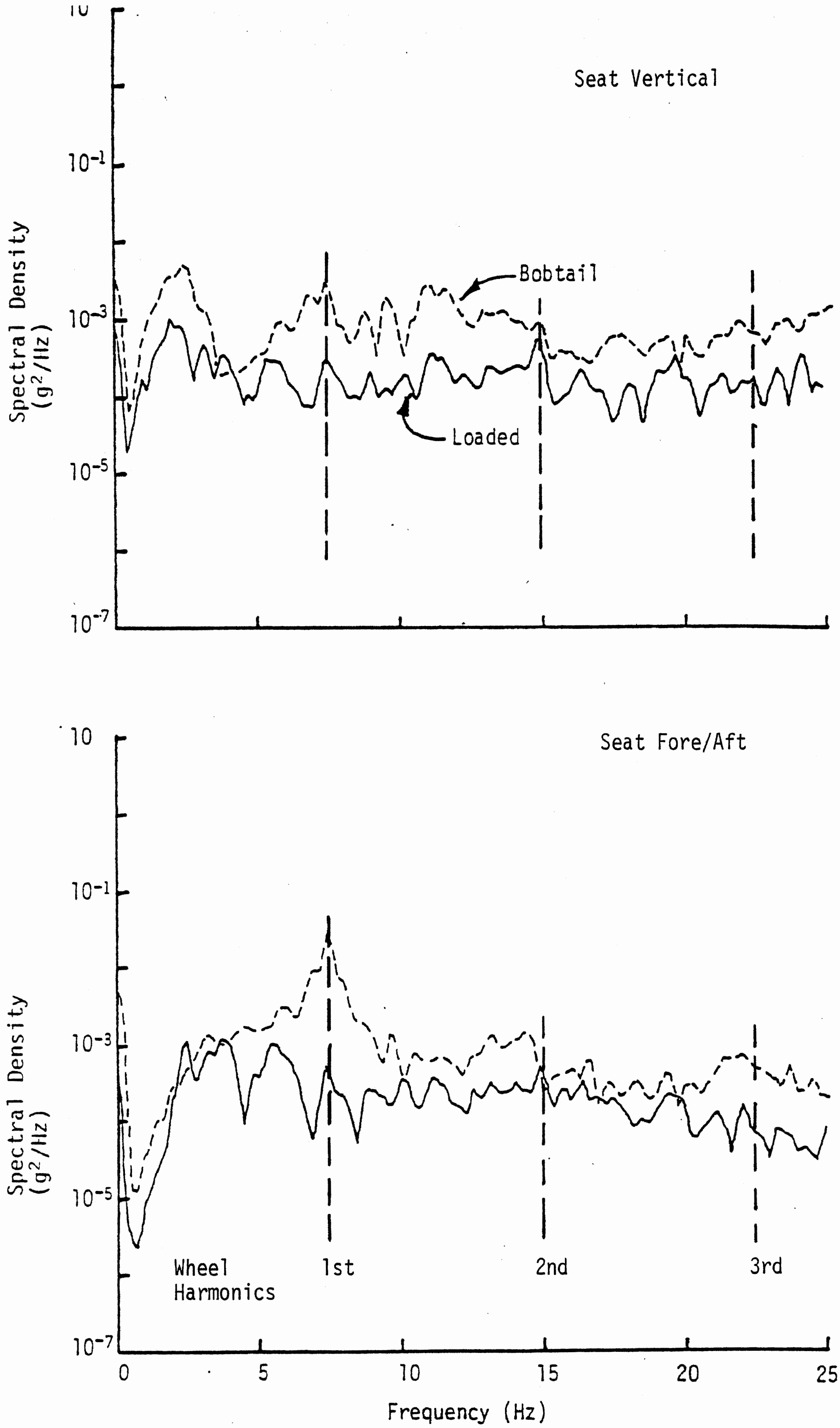


Figure 2.5. PSD's of bobtail vs. loaded combination - COE tractor, 55 mph, on a rough road.

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 2.6. 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 2.7, as calculated for a tractor-semitrailer (Dokainish, 1980).

An examination of Figure 2.7 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 2.8. 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.)

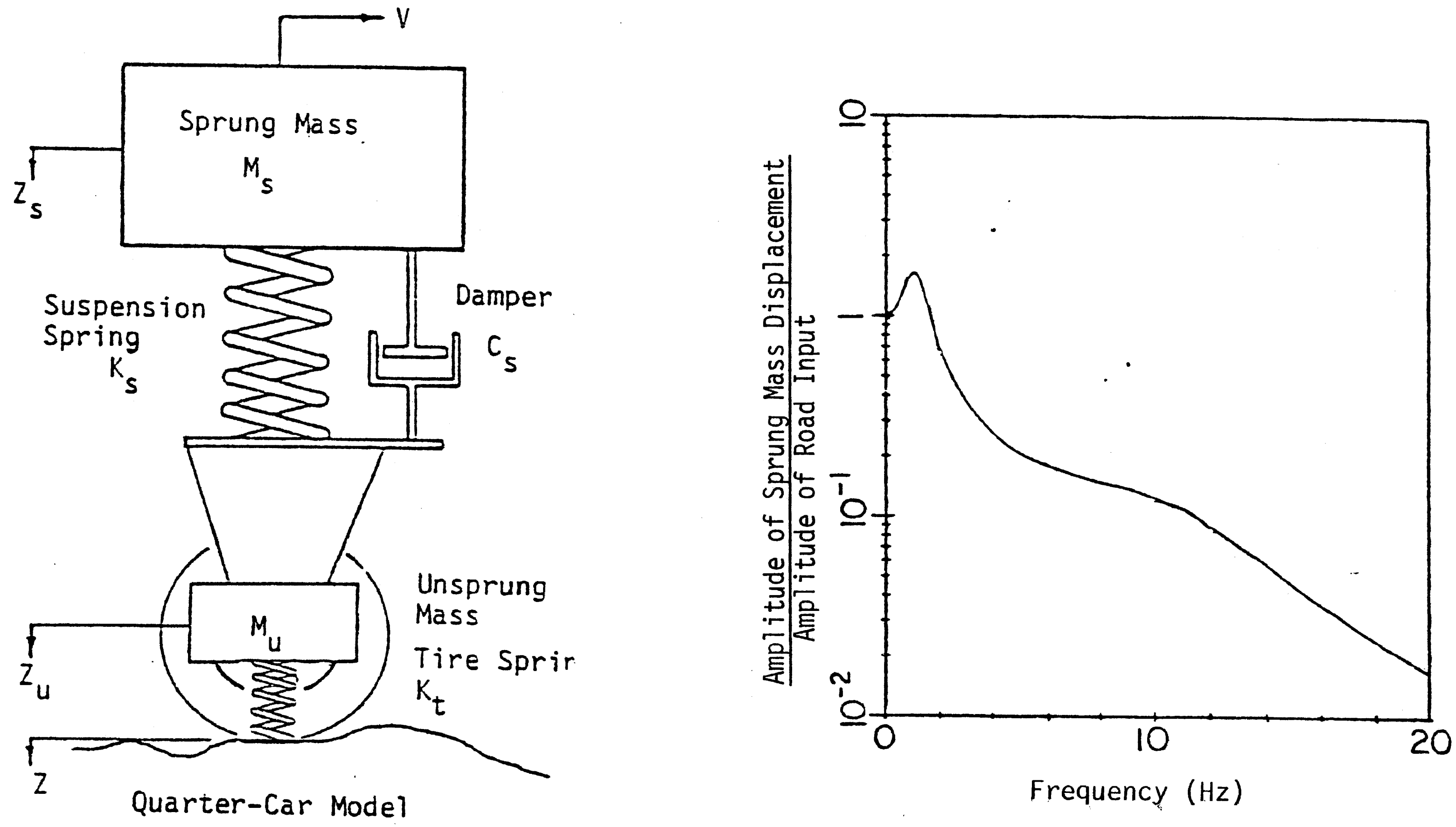
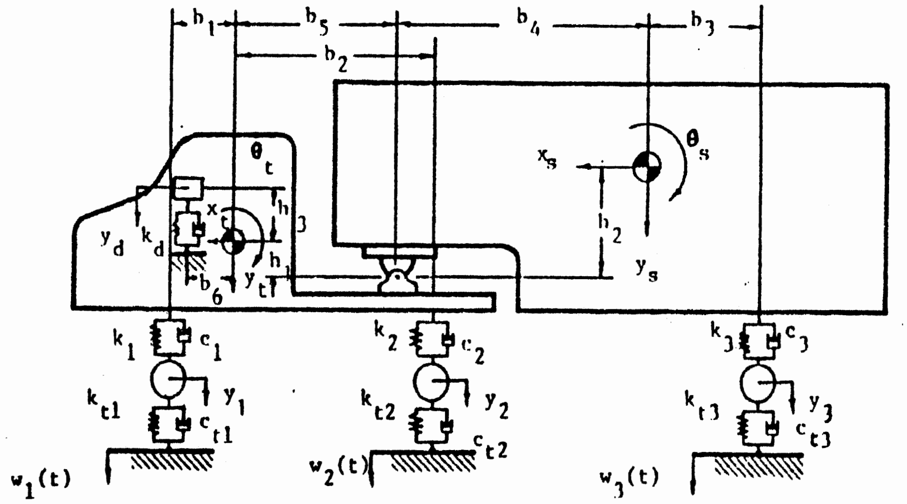
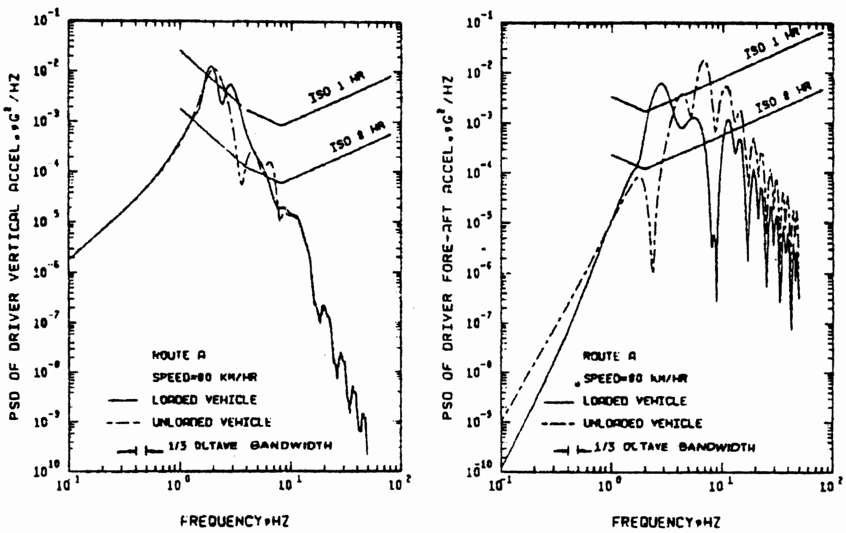


Figure 2.6. Isolation of a vehicle body from road input deriving from a quarter-car model.



Tractor-semitrailer model.



Vertical and fore and aft acceleration spectra – smooth road.

Figure 2.7. Calculated acceleration response of a multi-degrees-of-freedom tractor-semitrailer model to random road input.

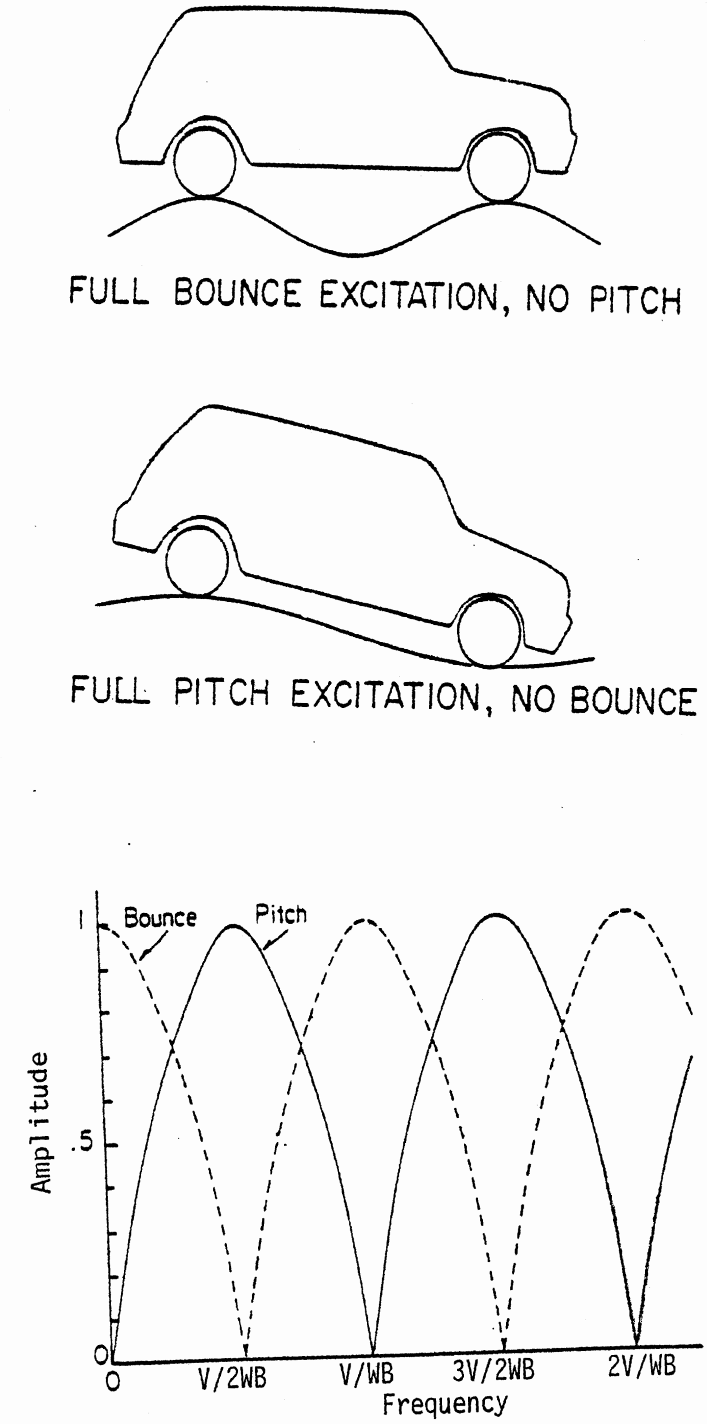


Figure 2.8. "Wheelbase filtering" causes a vehicle to not respond to certain road frequency inputs.

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 2.9, 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 2.10.

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.

2.3 The Truck Driver's Environment

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 implement 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,

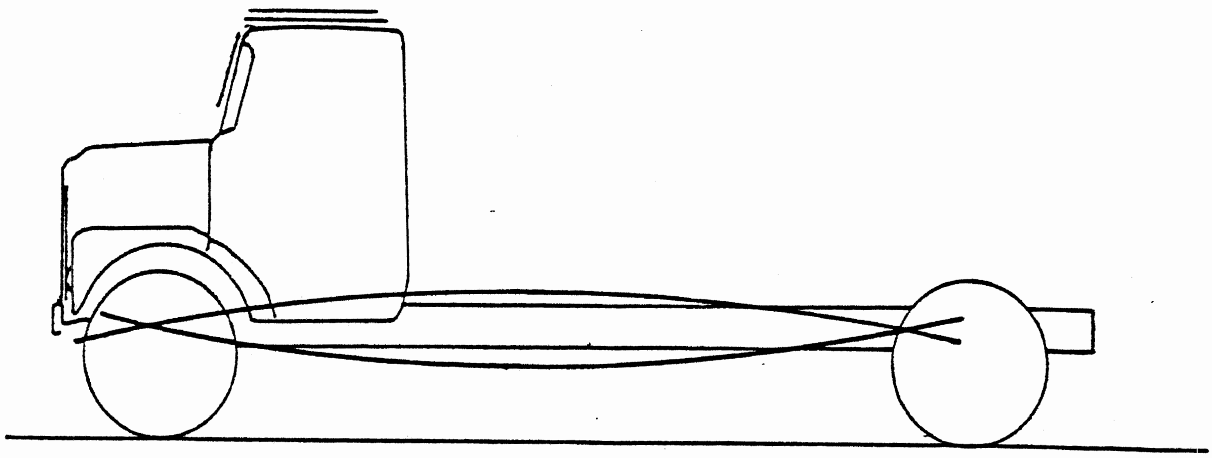


Figure 2.9a. Illustration of frame beaming vibration of a conventional cab truck.

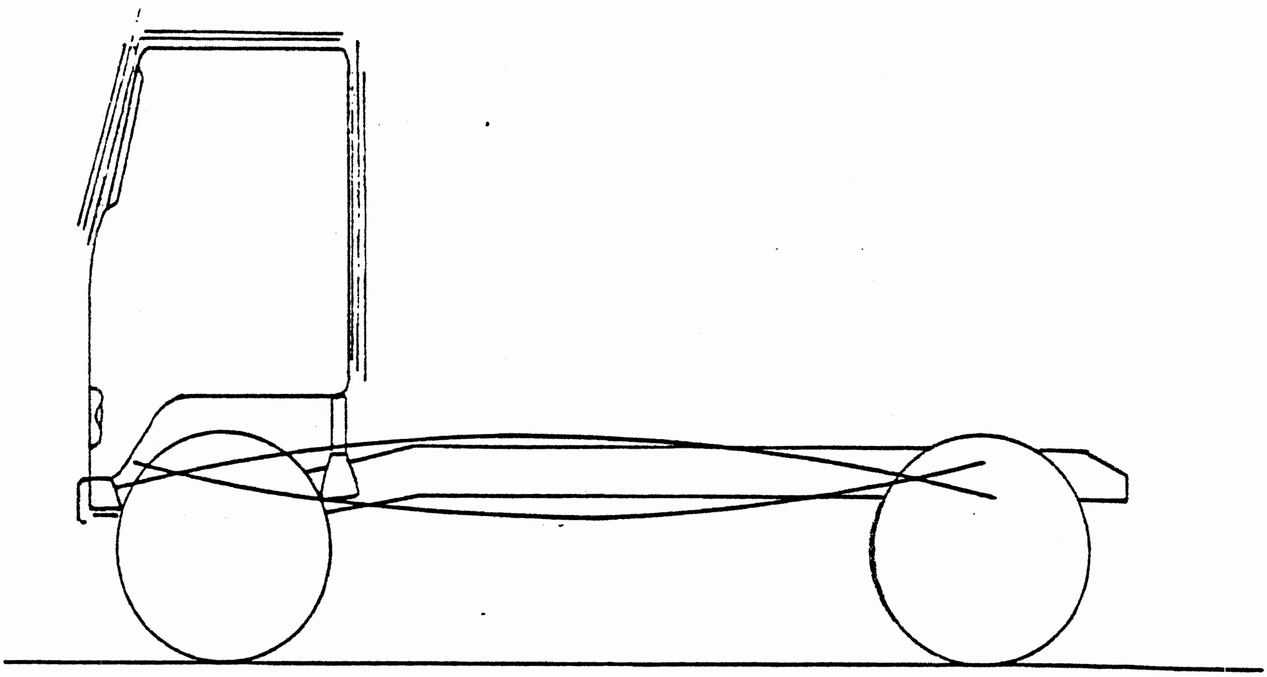


Figure 2.9b. Illustration of frame beaming vibration of a cab-over-engine truck.

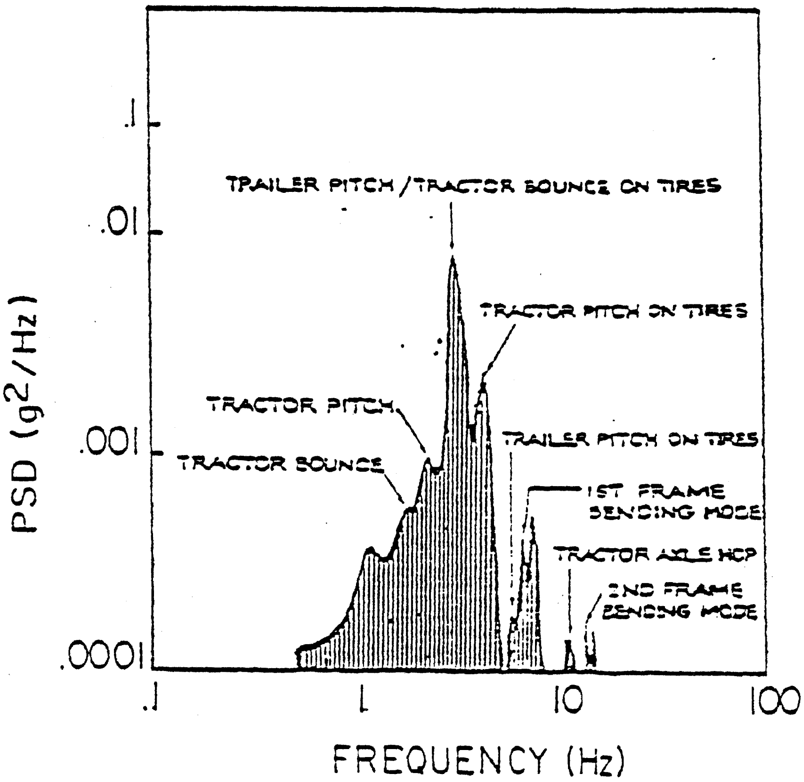


Figure 2.10. Typical PSD of vertical cab acceleration for a tractor-trailer (Crosby, 1974).

or even cause tires, steering, suspensions and other components to fail would most certainly constitute a safety hazard.

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 obscure 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 exists 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.

2.3.1 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 (perhaps) the most comprehensive picture of the accelerations present in commercial vehicles by providing a base of comparable measurements on a number of trucks under varying operating conditions. Figure 2.11 shows the vertical and fore-aft acceleration spectra which exist at the floor in the best and worse cases. The data have been 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 (in Figures 2.4 and 2.5) no significant attenuation of the spectrum was evident out through the upper frequency limit of 25 Hz. Thus, consistent data does 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 2.11, 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 2.4, 2.5, and 2.11, data obtained with another conventional tractor shows the same characteristic spectra, as demonstrated in Figure 2.12. 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.

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. 2.13). In general, the vertical component of acceleration tends to be

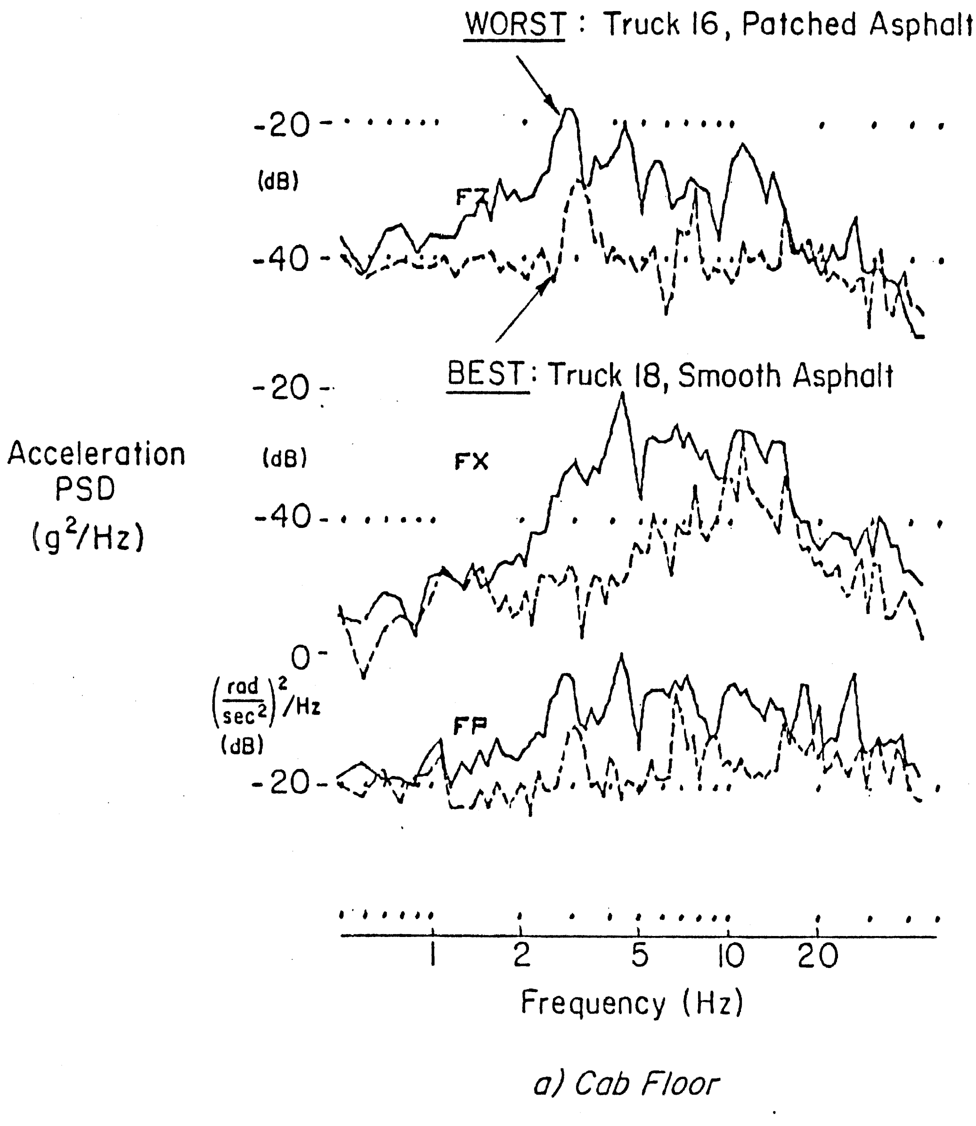
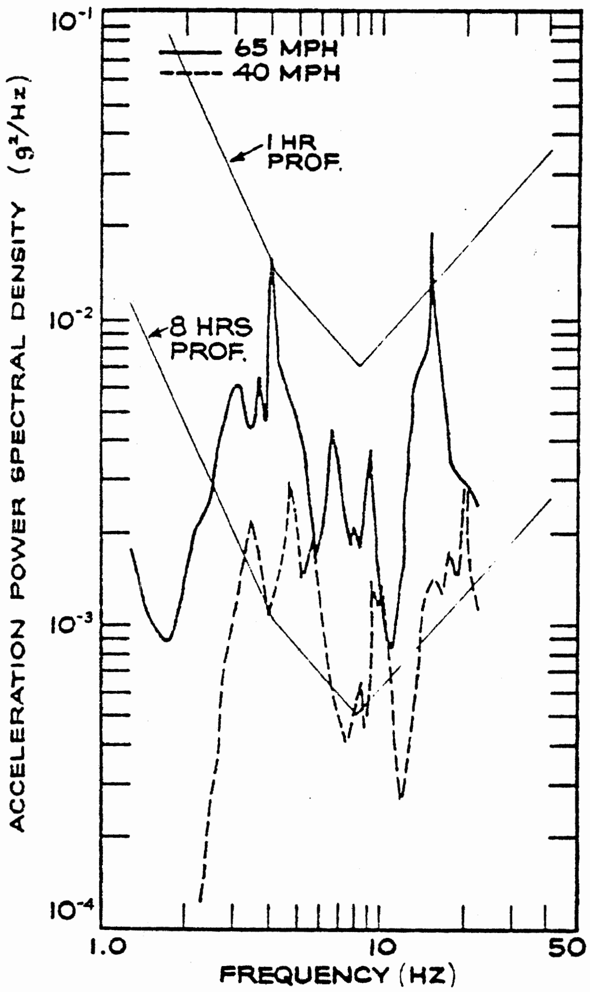
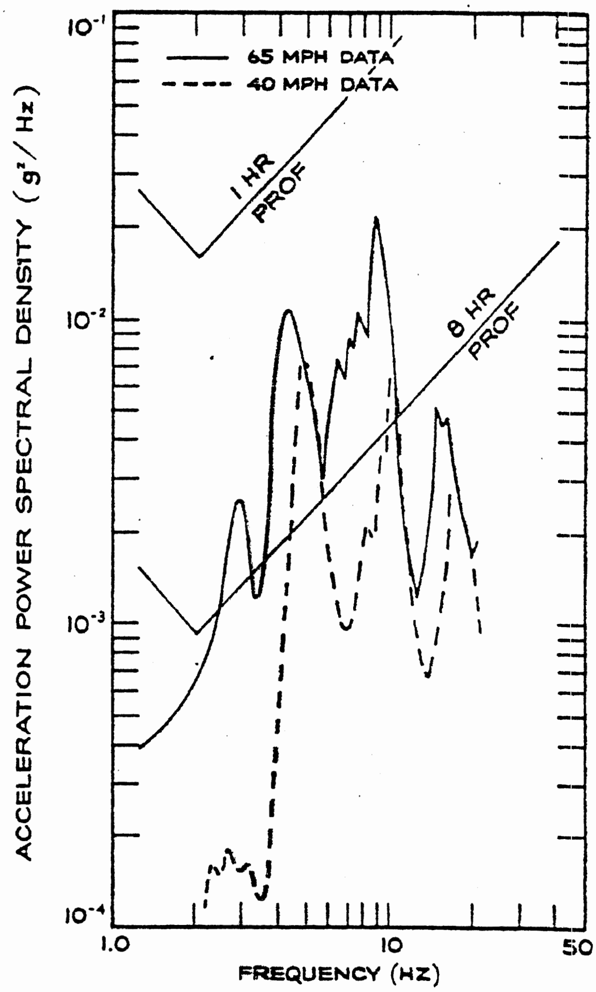


Figure 2.11. Typical best and worse case cab floor acceleration spectra on a tractor-semitrailer combination (Jex, 1981).



Vertical cab acceleration at rear of conventional cab–test data



Longitudinal cab acceleration at rear of conventional cab–test data

Figure 2.12. Typical cab floor acceleration spectra showing effect of different operating speeds. (Crosby, 1974)

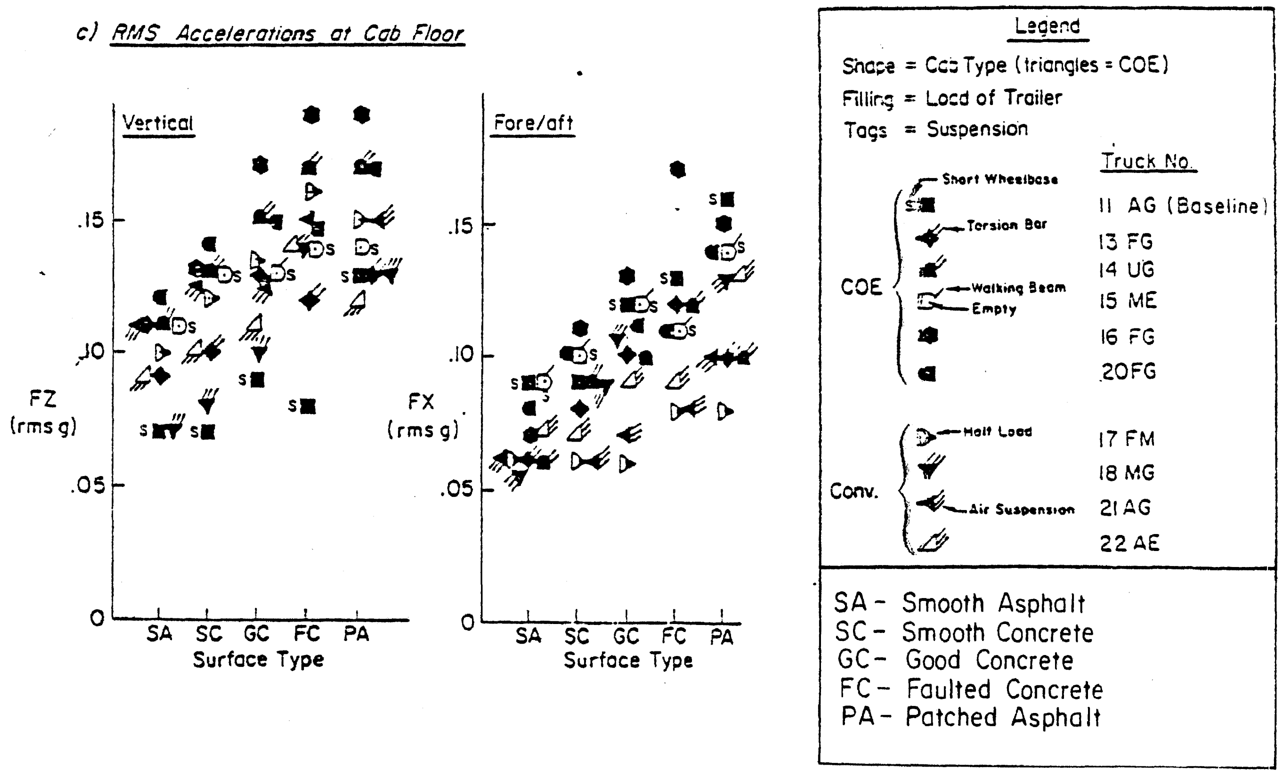
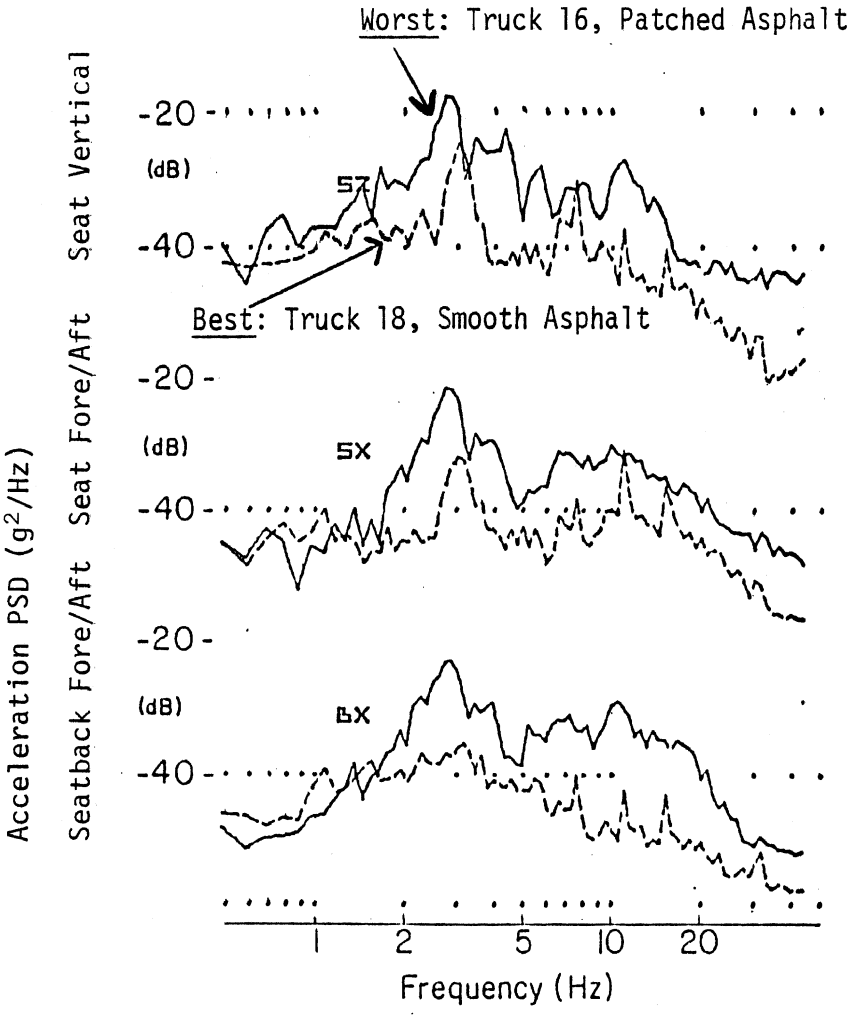


Figure 2.13. RMS acceleration levels measured on the tractor and cab floor of ten vehicles on five road types.

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.

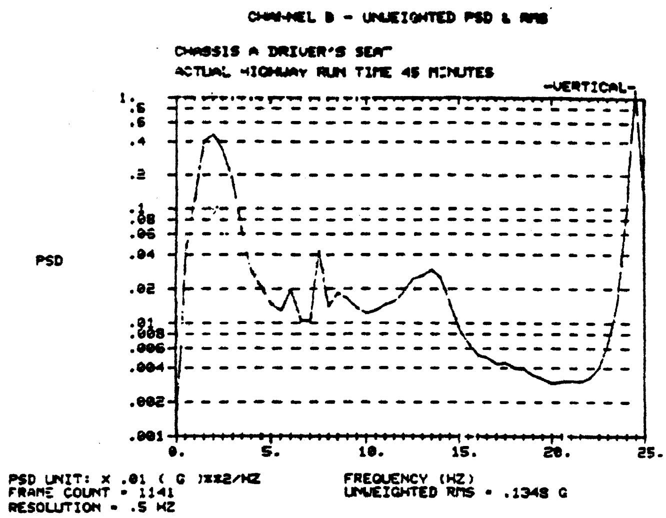
2.3.2 Direct Vibration Input Through the Seat. Limited data has been published in recent years which characterize the whole-body vibration input to drivers of highway tractors, as exist at the driver/seat interface. These data are broadly characterized by the acceleration spectra shown in Figure 2.14. 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 2.15 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. 2.15), like the long-wheelbase, conventional tractor (see Fig. 2.14), 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. The most broadly accepted summary measure of whole-body vibration environment appears to be the ISO-weighted value of RMS acceleration (ISO, 1974). Figure 2.16 shows that measure for the vehicles and conditions investigated in the FHWA project (Jex, 1981). On the basis of this method, most trucks and tractors appear to experience vibrations at levels considered acceptable for four to one hours of exposure, as measured against the Fatigue Decreased Proficiency (FDP) boundary. On the other hand, most of the vehicles and roadway conditions reflected in Figure 2.16 were subjectively rated by the driver as causing "none" to "mild" discomfort. Only the vehicle falling above the one-hour boundary was rated as causing "strong" to "extreme" discomfort. The small amount

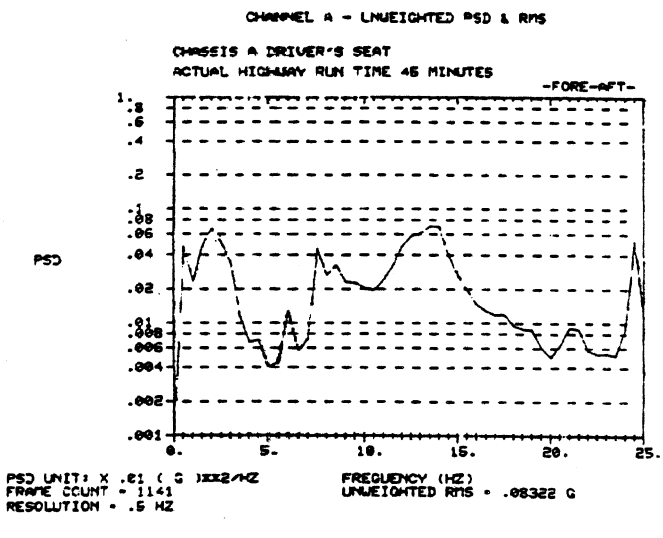


b) Driver Seat

Figure 2.14. 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 2.15. Typical seat acceleration spectra measured on a straight truck (Mehta, 1981).

b) ISO Weighted RMS Accelerations at Driver's Seat

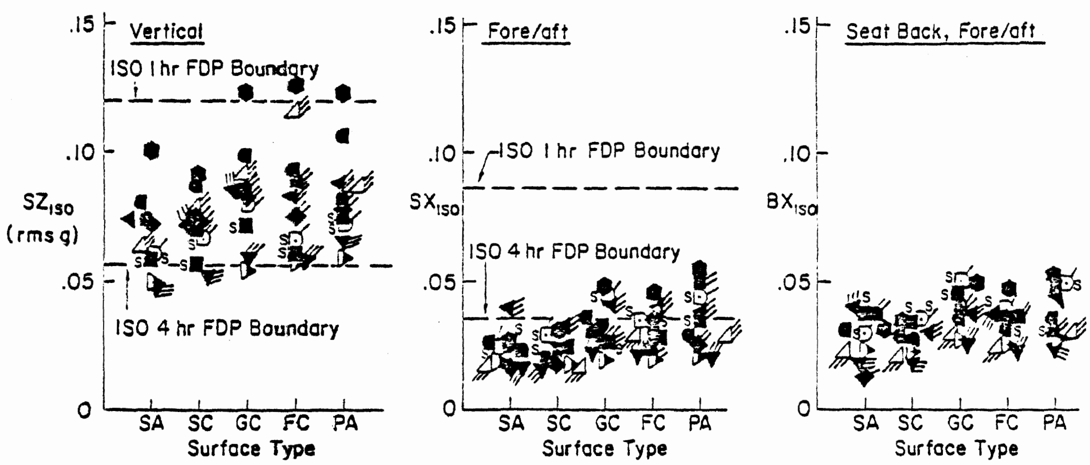


Figure 2.16. Weighted RMS acceleration levels on the seat of tractor-semitrailer combinations on different roads.

of data reported by Mehta (1981) in his study of straight trucks places them at about the four-hour FDP boundary with respect to vertical vibration for the particular test route used in that study.

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.

2.3.3 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 in his test program. From the little data that were reported, it appears that the top- and bottom-tenth percentile points are nominally 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- and bottom-tenth percentile level of 0.1 to 0.25 g's. These values, however, are likely to underestimate the 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.

Even with such data, however, it is difficult to infer what consequences can befall the truck driver as the data is 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.

3.0 EFFECTS OF VIBRATION ON MAN

3.1 Introduction

Section 2.0 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 in 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 the 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;

Wasserman, 1979; Grether, 1971). 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 3.1, 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.

3.2 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 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 neither 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.

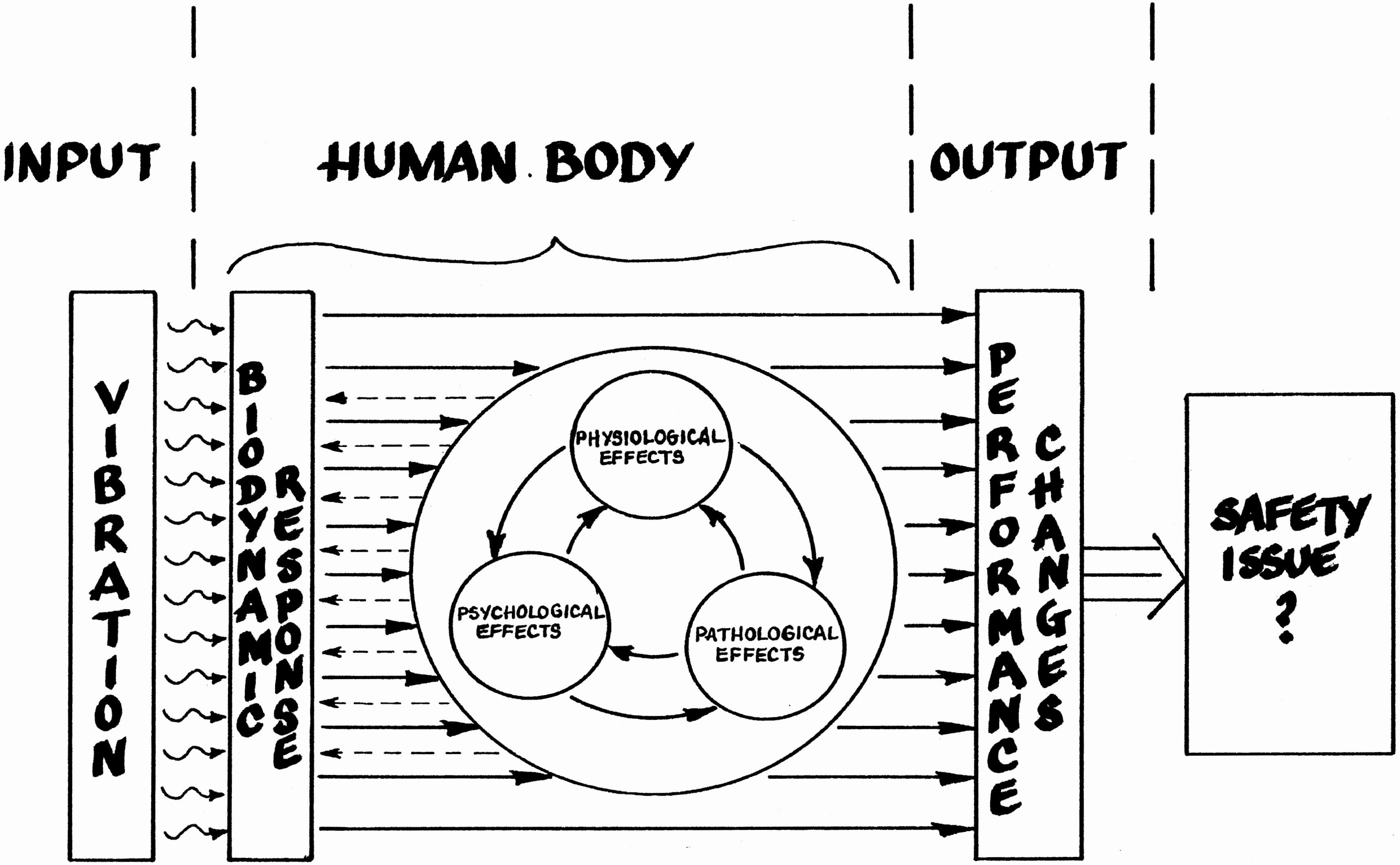


Figure 3.1. Schematic illustration of how vibration exposure may influence the human body and performance.

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 nondimensional measure of acceleration, namely, units of the earth's gravitational acceleration, where 1 g = 9.8m/sec^2. For sinusoidal stimuli, the acceleration may be reported either as the peak amplitude or as an average level (root-mean-square or 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 3.2. 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.

3.3 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, tissues 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, Figure 3.3), and (2) determine the transmissibility

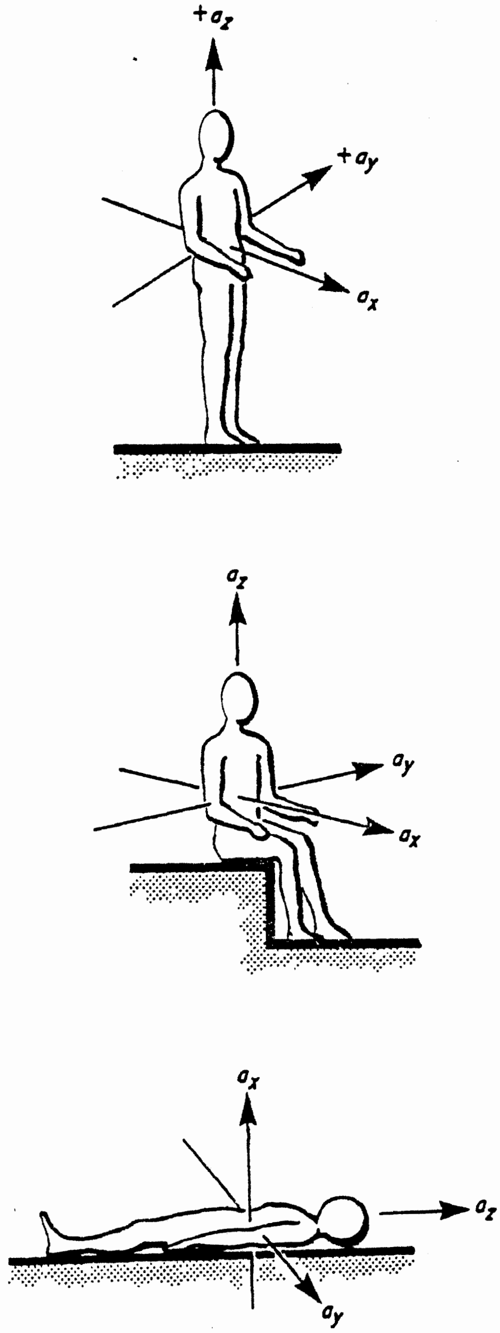


Figure 3.2. x, y and z axes used in vibration research
(from Wasserman, et al., 1979)

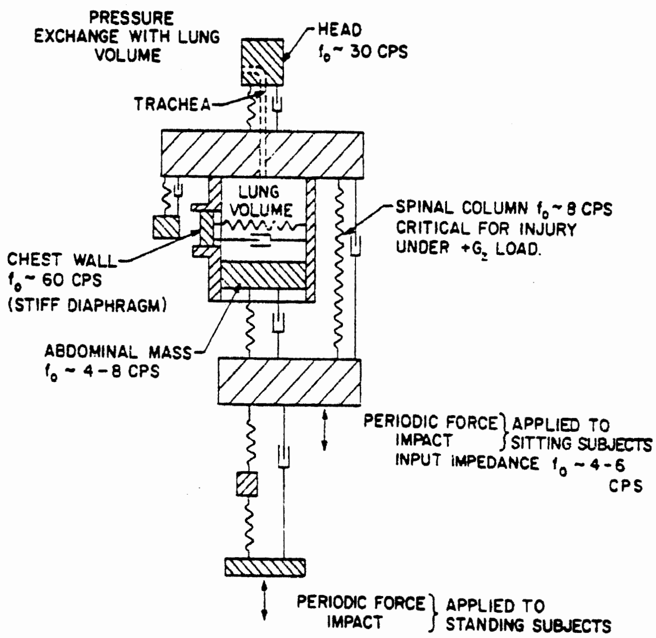


Figure 3.3. Mechanical model representation of human body exposed to vertical vibrations. (from Von Gierke, 1974)

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 simulus. 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 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 that may induce the following effects (Von Gierke and Clark, 1971):

1) discomfort as a result of large excursions of abdominal organs,

2) a sense of heaviness or fluttering of the stomach,

3) respiratory interference and motion of thoracic contents due to motion of abdominal contents against the diaphragm, and

4) speech impairment due to modulation of airflow through the lungs, trachea and larynx.

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.

3.4 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.

3.4.1 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 activity due to increased activity of skeletal muscle in maintaining posture and are interpreted as being similar to that caused by physiological response to

*Amount of air exchanged per minute.

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, although the mechanisms behind this response are not well understood. 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.

3.4.2 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.

3.4.3 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

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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).

activity may be the result of a vestibular or proprioceptive reflex which tries 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, 1974). 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 3.4, 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, the long-term effect may be increased fatigue.

3.4.4 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 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.

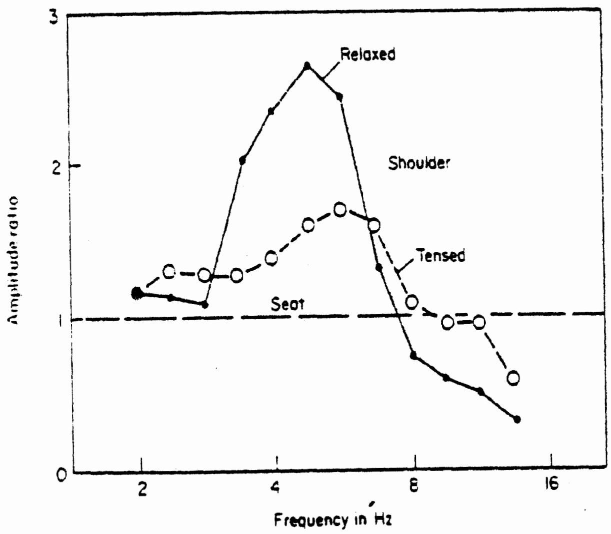

Figure 3.4. Effect of muscle tension on amplitude of shoulder vibrations (after Guignard, 1965)

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.

3.5 Psychological Effects

3.5.1 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. While 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, it is largely these types of studies which led to the ISO Standard 2631, "Guide for the Evaluation of Human Exposure to Whole-Body Vibration." As shown in Figure 3.5, this standard sets forth boundaries for exposure to vibration as a function of frequency, duration, intensity and direction of the stimulus. Different sets of boundaries are defined for (1) exposure limits (e.g., health and safety), (2) fatigue-decreased proficiency, and (3) comfort. Shapes of the curves, as a function of frequency, are the same for all three cases and reflect the biodynamic resonances of man as discussed earlier. The magnitude of the "fatigue-decreased-proficiency" boundary is obtained by multiplying the "reduced comfort" boundary by 3.13 (10 dB) with the "exposure limit" boundary being 2 (6dB) times the proficiency level boundary.

Another attempt at describing human subjective response to short-term vibration exposures was compiled by Goldman utilizing the results of Ziegenruecker and Magid (1959). Again the results show the greatest sensitivity and least tolerance in the range of 2 to 8 Hz, as illustrated in Figure 3.6.

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, they can

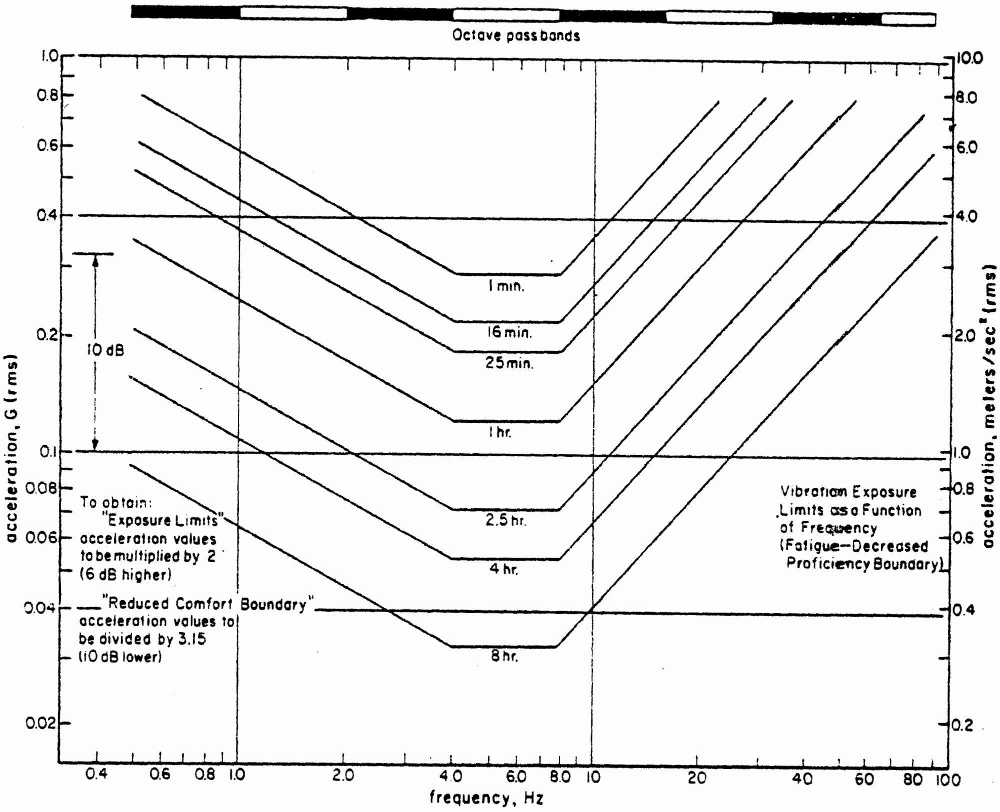

Figure 3.5a. ISO vertical vibration exposure criteria as a function of frequency-fatigue-decreased proficiency boundaries. (Von Gierke and Clark, 1971)

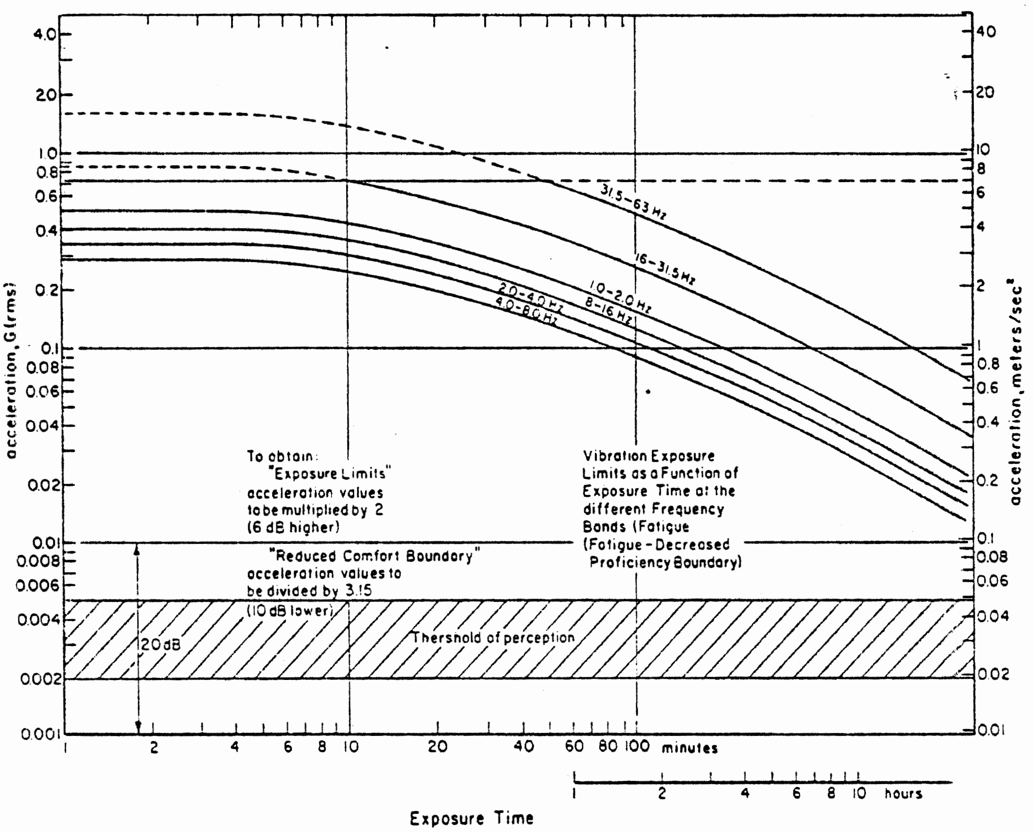

Figure 3.5b. ISO vertical vibration exposure criteria as a function of total daily exposure-fatigue-decreased proficiency. (from Von Gierke and Clark, 1971)

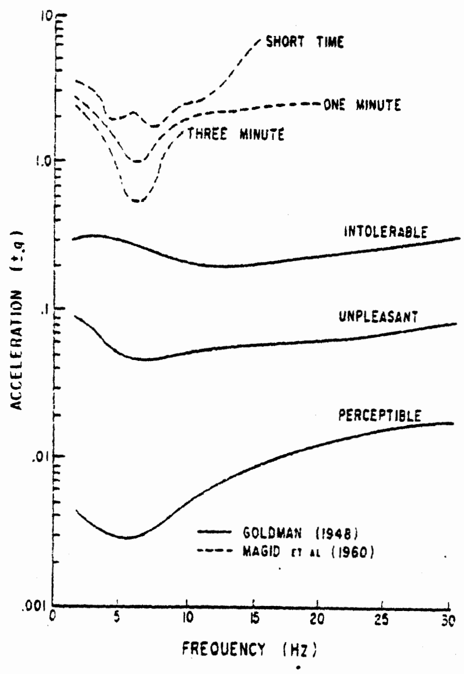

Figure 3.6. Goldman's composite subjective response curves and z-axis voluntary tolerance curves of Magid, et al, 1960 (after Chaney, 1964 and Shoenberger, 1972).

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." The ISO standard indicates that a truck driver who experiences vibration having an intensity of .05 g's RMS in the vicinity of 6 Hz would be exposed to a "reduced comfort" condition after a short time interval. The standard further indicates that a driver would experience a decrease in his proficiency after four hours of exposure to this level of vibration. At a level of .15 g RMS, a decrease in proficiency would be expected after an hour or less.

3.5.2 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 out-weighs 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 far exceeding that of the truck driver's environment.

3.6 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 most likely to occur at vibration magnitudes in excess of 2 g's and thus acute effects are not an issue in the context of driving a truck. Chronic effects, on the other hand, are the long-term health problems which result from repeated exposure to moderate, but not immediately damaging, levels of vibration. While it is extremely difficult to establish clear correlations between long-term exposure to vibration and decreased health due to a large number of other contributing and complicating factors, the consensus of epidemiological research is that a disproportionate number of certain health problems do occur in workers exposed to vibration. Table 3.1 summarizes some of these disorders.

There are data which suggest that drivers of rough-riding vehicles such as tractors, earthmovers, and military cross-country vehicles show a higher incidence of certain diseases and disorders such as spinal

Table 3.1. Selected Epidemiological Studies and Results. (Based on Pepler and Naughton, 1980)

Date	Author	Occupational Conditions	Medical Condition Prevalent in Occupation	Conclusions (Connection with Vibration)
1964	Andruna-Gelanina	Mining Operations	CNS misfunction	Adverse effect of whole-body vibration over extended periods of time (e.g., continued exposure for 8-hr periods)
1960	Rosseger, Rosseger	Tractors	Spinal cord disorders (e.g., osteochondrosis, spondylosis)	Vibration and poor posture; conditions increase as function of driving time
1972	Dupuis, Christ	Tractors (10 yr. follow-up)	Spinal cord disorders	Results; same as Rosseger, Rosseger, 1960 (see above)
1974	Mulby, Spear	Heavy Equipment Operators	Ischemic heart disease, obesity of non-endocrine origin, musculo-skeletal diseases (e.g., displacement of intervertebral discs)	Selection process in which members of the exposed group leave jobs that subject them to whole-body vibration when they become afflicted
1974	Gruber, Ziperman	Bus Drivers	Varicose veins, hemorrhoids, acute respiratory infections, abdominal and back disorders (e.g., peptic ulcer, appendicitis, colitis, gastro-enteritis), kidney diseases, musculo-skeletal diseases (e.g., displaced intervertebral discs, ankylosis, vertebrogenic pain syndrome)	Resonance of trunk of the body under vibratory condition held responsible
1975	Kelsey; Hardy	Truckers	Herniated lumbar disc	Truckers about 5 times more likely to develop
1974-1976	Spear, et al.	Heavy Equipment Operators	Ischemic heart disease, displaced intervertebral discs, disease of male genetalia	Syndromes tied to vibration exposure

Table 3.1 (Cont.)

Date	Author	Occupational Conditions	Medical Condition Prevalent in Occupation	Conclusions (Connection with Vibration)
1976	Gruber	Interstate Truck Drivers	Obesity	No association.
			Nervous stomach	Frequency associated with physiological responses to sustained psychosocial stress.
			Hypertension	Mater-of-degree disorder; excess of condition probably artifact of selection by medical examiners.
			Hemorrhoids	Confinement to seat and resonance truck vibration.
			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.
			Appendicitis	Vibration may be factor in etiology.
			Kidney disease	Strong seat vibration has diuretic effect.
			Diseases of male genitalia	Vibration may be factor in etiology.
			Pilonidal cyst	Vibration may be factor in etiology.
			Vertbrogenic pain syndrome	Vibration along z-axis.
			Bone deformities	Vibration along z-axis.
			Sprains, strains	Vibration along z-axis.
1978	Troup	Truckers	Back pain	Posture and vibration are both factors.

problems (e.g., low back pain), ano-rectal and gastro-intestinal ailments, kidney disease, hemorrhoids, pilonidal cysts, musculo-skeletal disorders, and certain diseases of the male genitalia. However, kidney disease is the only major long-term health effect attributed solely to vibration exposure as a result of supposed diuretic effect of motion stimuli. But, in fact, the greater number of kidney problems reported by truck drivers may also result from a combination of factors such as prolonged sitting times and increased caffeine intake.

In occupations where vibration is a factor, subjective methods have been used to determine health effects of shock and vibration. For example, in a survey of the International Brotherhood of Teamsters and the Professional Driver's Council, one-third to one-half of the questionnaire respondents reported ride quality (shock and vibration) problems and 85 percent of the IBT respondents felt certain health problems were either directly or indirectly related to ride quality (Pepler and Naughton, 1980).

It seems that vibration may, indeed, play a role in the etiology of certain ailments which are more prevalent in the occupation of driving a truck than in occupations where vibration is not a factor, but vibration has, clearly, not been singled out as a primary, let alone sole, cause. Consequently, the only conclusion that can be made at this time is that a person in a vibration-related occupation may have a greater risk of developing certain ailments than a person in an occupation where vibration is not a factor.

3.7 Performance Changes Due to Vibration Exposure

3.7.1 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 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.

3.7.2 Visual Acuity. There is a general consensus in the literature that exposure to whole-body vibration at frequencies ranging from 10 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 appears 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 is 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 decrement due to limits in compensatory eye movements.

3.7.3 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 vibration.

3.7.4 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 as (1) being of "poor quality" and (2) using a "diverse methodology" 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 experimenters 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.

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 or no effect on visual acuity with respect to fixed objects at a distance,

4) a loss 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," but no measurable change in mental stress,

6) increased fatigue after four hours of exposure,

7) possible (but not probable) increase in certain pathological disorders, such as kidney disease and 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.

4.0 DOES RIDE VIBRATION CONTRIBUTE TO THE ACCIDENT FREQUENCY OF TRUCKS AND TRACTOR-TRAILERS?

4.1 Introduction

The evidence (summarized above) suggests that there are several ways in which the vibration environment in a truck cab can lead to decrements in driving performance of possible consequence to motor carrier safety. One 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 occurrance 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 can occur with long-term exposure to vibration. If after several years of driving, a trucker suffers from physical ailments such as low back pain or gastrointestinal disorders, 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.

Finally, a sixth way in which ride 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 evidence which addresses 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 that six different vibration mechanisms (as identified above) 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 is 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 during calendar year 1978, since this is the latest year available in all of the data files that were examined. Subsequent to this overview, an effort is made to interpret the data with respect to the possible impact of ride vibration on accident involvement.

4.2 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 vehicles registered in the United States. These vehicles accounted for 0.9 percent of all vehicles registered in 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).

Table 4.1 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

Table 4.1. 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)

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 4.2 shows the distribution of tractor combinations by fleet size. Fleet size is defined in 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 mileages 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 4.3 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 4.3.

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 4.3 in order of increasing wheelbase length. Tractors with a shorter wheelbase generally produce a more severe ride as compared to those with a longer wheelbase. Table 4.3 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 4.2. Distribution of the Number and Mileage of Tractor Combinations by Fleet Size*.

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

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

Table 4.4 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.

4.3 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, 4231 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 (4746). 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.

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 these figures will show a decrease of about 15 percent for 1980.

Table 4.4. 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)

A breakdown of fatal accidents by collision type is given in Table 4.5. 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 ascribable to 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 4.5 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 4.6. 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 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 accrue about 81 percent of their mileage on rural roads, while passenger cars accrue 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

Table 4.5. 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 4.6. 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)

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, 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 4.7. 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 reasonably consistent with the percentage of combination vehicle mileage accrued by the authorized carriers, namely, 42.9 percent, as shown in Table 4.1. 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, accident files prepared by the States of Michigan, Pennsylvania, Texas and Washington (as maintained at HSRI) have been examined to estimate a

Table 4.7. 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.

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.

4.4 Evidence of the Effects of Ride Quality on Accident Involvement

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 vehicle. 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 2 percent of the accidents reported in Texas and less than 0.2 percent in Washington. (The passing vehicle, car or truck, is not identified.) Thus, since passing accidents, in general, seem to be rare, the available accident data suggest that mirror vibration is not a significant contributing factor to accident involvement.

Earlier, it was suggested that the vibration environment in the cab of a truck (or truck tractor) 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 4.8 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 4.9 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, the Texas file codes "foot slipped off clutch or brake" under "contributing circumstances." This factor is indicated in less than 0.1 percent of the accidents. 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 4.8. 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 4.9. 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 4.10. 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 4.11 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 only three fatal accidents involving a combination vehicle. (This finding should be tempered by the fact that roadway maintenance or construction was reported as a contributing factor in 44 fatal accidents involving combination vehicles in that same year.) It would appear, then, 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 designate "fatigue" as a factor, rather he is constrained to indicate that the driver was "asleep" or "ill." Table 4.12 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 4.13 shows a further breakdown of <u>single-vehicle</u> 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

Table 4.10. 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 4.11. 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 4.12. 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 4.13. 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%

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 is shown in Table 4.14.

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 4.15 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 4.15 occurred when the driver had been on duty four hours or less. The number of drivers that were reported to have been sick or to have dozed at the wheel is also shown in Table 4.15 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 4.15 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.

4.5 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 involvement.

Table 4.14. 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 4.15. 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

2. Information on the national population of combination vehicles indicates that cabover-style tractors are used more extensively in long-haul service. Hence, the tractors which exhibit somewhat more severe ride vibrations are likely to involve longer driving periods. In this instance, fatigue—as arises from vibration and other sources—appears to be a relevant concern.

3. Although the available evidence is very limited, accident data suggest that short-term vibratory effects—degraded rear vision, driver disengagement from vehicle controls, a reduced proficiency in control modulation, and degraded road holding—are _not_ significant factors contributing to motor carrier accidents, notwithstanding laboratory findings which suggest impairments in driver control skills.

4. 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.") Research is needed to identify how this synergism leads to driver failure to perform the driving task, either at the mechanistic level or at the psychosocial level, or both.

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