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DETERMINATION OF IMPACT FROM VIBRATIONS RELATED TO HIGHWAY USE

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16. Abstract

This report describes the results of a study to determine the environmental impact from traffic-induced ground vibration. The study encompassed psychological, legal, and engineering efforts to define the nature and extent of the problem. At the beginning of the study, there was no published literature directly related to describing either the engineering aspects or applicable criteria to evaluate the impact of traffic-induced vibration. Litigation, however, had occurred in the United States.

The results of this study have clarified the nature and extent of traffic-induced vibration. Traffic-induced vibration is, generally, an urban problem. Generally, the owner-resident of a building is the annoyed party. It appears that traffic-induced vibration is not of sufficient magnitude to generally cause structural damage to buildings. However, old buildings of an historic character may be a special concern.

The main text of this report summarizes the detailed results of the study. Appendicies are included presenting the detailed results.

A companion report is entitled: "Engineering Guidelines for the Analysis of Traffic-Induced Vibration", U.S. Department of Transportation, Federal Highway Administration Report No. FHWA-RD-78-166, June 1978.

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METRIC CONVERSION FACTORS

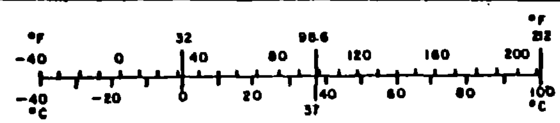
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

This report describes the results achieved for a program to determine the impact from vibrations related to highway use. These results are based upon a detailed literature review, technical analyses, and field test measurements all related to the topic of environmental vibration resulting from traffic movement on highways.

As described in the following sections, the effort reported herein places many aspects of the highway-induced vibration problem in perspective. In particular, it is indicated that traffic-induced vibration problems are not new but that both the frequency of occurrence and the frequency of damage awards to a plaintiff appear to be increasing on an annual basis in the United States. By assembling data reported in the literature, quantitative bounds describing the vibration levels and frequency content required for human perception and building damage are presented. By assembling complaint data compiled as a result of this effort and assessing the documented legal precedents resulting from court actions, quantitative assessment of what the public complains about and the courts' judgement about these complaints is presented.

By analogy with community noise, traffic-induced vibration requires a description of level, frequency content and time variation for proper definition of the vibration. Whereas, a community can be exposed to significant transportation system noise on a large geographical scale, transportation system environmental vibration is much more confined. As a result, public officials do not receive apparently as many complaints related to vibration as compared to complaints related to noise, but vibration complaints are more persistent and the likelihood of receiving damage awards is greater than the corresponding situation with noise. Concern over community noise has resulted in defined criteria and standardized instrumentation and measurement techniques. Such defined criteria and standardization do not presently exist for environmental vibration in general or traffic-induced vibration in particular.

The problem of traffic-induced vibrations causing public annoyance and/or building damage is a problem that is being experienced in urban areas of industrialized countries and is presently a recognized environmental consideration. As reported by investigators in England, Czechoslovakia, the USSR, Japan and as concluded from the study reported herein for the United States, the problem of traffic-induced vibration is increasing on an annual basis.

The organization of this report is such that the main body presents a condensation of the data and results of more extensive investigations. The details of particular data and the detail discussion concerning a particular topic is included in the appendices of the report as noted.

2.0 OBJECTIVE, SCOPE, AND APPROACH

The main objectives of this research program are:

- Clarify the nature and extent of the traffic-induced vibration problem by improving the understanding of vibration excitation, propagation and effects.
- Develop guidelines to preclude or control environmental vibrations devoting special attention to the traffic-induced vibration situations resulting in complaints and/or litigation.

The scope of this research program is limited to the role of highway operations in generating environmental vibrations. The examination of parameters describing traffic-induced vibrations includes consideration of

- Vehicle-pavement interaction
- Structures sensitive to vibration
- Activities sensitive to vibration.

For this program the dynamic characteristics of vehicles are to be considered only in relation to their vibration-producing interaction with the highway pavement. Vibration sensitive structures and activities are considered to be only those likely to be located in the proximity of the highway.

To fulfill the objectives of this research program, eight basic tasks have been defined. These tasks are:

- TASK A: Literature Review and Evaluation
- TASK B: Complaint Assessment and Problem Definition
- TASK C: Analysis of Highway Vibration
- TASK D: Field Testing
- TASK E: Isolation (Abatement) Techniques
- TASK F: Development of Design Guidelines
- TASK G: Develop Simplified Measurement and Data Reduction Procedures
- TASK H: Refinement of Traffic Flow Model.

2.1 Task A, Literature Review and Evaluation

Environmental vibration resulting from highway traffic has been investigated for the past 30 years (Bernhard (1941), Southerland (1950)) with the most interest - as reflected by published literature - being expressed in the past four years. The problem has arisen as a result of occupant annoyance and alleged building damage and/or destruction related to the movement of heavy highway vehicles along streets and highways in the proximity of the buildings (Southerland (1950), Bata (1971), Whiffin and Leonard (1971), House (1973), and Tokita (1973)). These references indicate that the problem of traffic-induced vibration is a growing environmental problem related to the long-term exposure of structures to seismic foundation motion and that the problem can be expected to worsen if left unresolved. Fortunately, as result of the present literature review and evaluation many of the detailed considerations related to the various aspects of traffic-induced vibration have been assembled, summarized, and placed in perspective. This section describes the objective, approach, and results of Task A, Literature Review and Evaluation.

The objective of the Literature Review and Evaluation is to review and to evaluate previous and current studies on vibration excitation and propagation from the highway source to the receiver to determine the effects of vibration on structures and humans.

This task included a review of literature in the following topics classified in relation to either source characteristics, path characteristics, receiver characteristics, or legal literature:

Source Characteristics:

- Highway Traffic-Induced Vibrations
- Railway and Subway Vibrations
- Construction and Blasting Impacts
- Sonic Booms

Path Characteristics:

- Vibration Propagation and Attenuation

Receiver Characteristics:

- Geological Survey Techniques
- Vibration Criteria
- Human Threshold Levels for Vibration Perception
- Human Response to Vibration Spectra and Levels

Legal Literature:

The detail topic classification used for the literature review and evaluation is presented in Table AI-1 of Appendix I.

As defined by the scope of this research program, literature defining the role of highway operations in generating environmental vibrations and literature providing analyses and data related to the basic topics listed above were given primary consideration. Basically, the literature review encompassed both a computer search, provided by the Contract Manager, using TRIS and efforts in scanning abstracts, locating source material, and reviewing individual papers or reports.

As each literature source item was reviewed, a brief annotation was made of the contents of the item with emphasis being placed upon identifying specific data or results applicable to the description of traffic-induced vibration resulting from highway operations. The literature so reviewed was cataloged by topic - as described in Appendix I. The annotated bibliography resulting from the literature review and evaluation is presented in Appendix I.

Currently, the annotated bibliography presented in Appendix I lists over 200 technical sources classified in relation to the highway vibration problem. This listing is not to be considered as final since the literature review and evaluation is a continuing program task as indicated by Figure 2-1. Additionally, the bibliographies presented in Appendix III on Law, and in Appendix IV on Human Response, supplement the listing in Appendix I.

The Engineering Guidelines, developed under Tasks E through H, present additional technical references concerning traffic-induced vibrations (1)*.

* Numbers i ( ) denote references listed at the end of the report.

2.2 Task B, Complaint Assessment

In order to define the nature of the problem for traffic-induced vibrations, it is necessary to establish the occurrence and frequency of complaints or litigation associated with traffic-induced vibrations. In particular, it is necessary to define the problem for the highway environment in the United States.

As reported in the literature, much of the emphasis for studying traffic-induced vibration has resulted from building damage to historic property in Europe (Bata (1971), Whiffen and Leonard (1971), House (1973)). In Japan, traffic-induced vibration is being assessed in relation to other environmental seismic vibration sources such as railway lines, manufacturing processes, etc. (Tokita (1973)). Similar studies have been reported by Barkan (1962) in the USSR. Although previous investigators have studied the problem of traffic-induced vibration in relation to their respective national communities, it is problematical that their efforts properly define the corresponding situation in the United States. Hence, the main objective of Task B of this research program is to provide a definition of the traffic-induced vibration problem as encountered by highway planners and designers in the United States.

Initially, the approach selected to determine the occurrence of traffic-induced vibration complaints was to develop a questionnaire to survey public officials directly involved with highway planning, design and maintenance. However, after reviewing the schedule limitations for this task, it was mutually decided by the contractor and FHWA Contract Manager that a direct approach aimed at locating specific complaint data would be of more benefit to this program.

The approach taken was to contact, as assisted and directed by FHWA Contract Manager, Regional FHWA offices to determine any situations that might have come to their attention related to either complaints and/or litigation resulting from traffic-induced vibrations. Each Regional FHWA office then directed the inquiries to the appropriate State FHWA offices, and municipal agencies. This approach allowed a direct contact with concerned public officials regarding specific situations that had been and are currently being experienced in the field.

Following a contact sequence beginning with FHWA Regional offices and ending with State DOT offices, the complaint data centered around environmental considerations during highway planning and operation. Complaint data resulting from contacts with municipal agencies totally centered around highway operational situations. FHWA and State DOT contacts identified 29 situations and municipal contacts identified an additional 39 situations. Of the situations identified, 51 cases were well documented and 17 were not. All municipal contacts indicated that they had experienced some form of complaint related to traffic-induced vibration (the 39 situations indicated above resulted from a 45% response of municipal agencies contacted).

In order to classify the highway vibration complaint data, two basic categories were used: planning considerations and operational complaints. Planning considerations are taken to be those statements of concern related to traffic-induced vibrations voiced by citizens during the planning stage of highway design. Operational complaints are complaints related to traffic-induced vibrations voiced by citizens as a result of traffic operations on highways or streets.

All complaint data related to planning considerations were obtained from the FHWA Regional Office and State DOT contacts. These cases represented a total of 10% of all complaint data and related to proposed highway alignments near existing buildings. The cases involved two hospitals, two observatories, one school, one apartment building, and one office building. Except for the highway alignment near the observatories all concerns were apparently alleviated so as not to adversely affect the highway design. However, the two observatories, in conjunction with local environmental and neighborhood groups, blocked the development of a state tollway using traffic-induced vibration, air pollution, and noise as a basis for emphasizing the adverse impact of the proposed highway alignment. (It was alleged that traffic-induced vibration would have disrupted the observatories capabilities to make long-term photographic exposures as a result of traffic-induced vibrations causing the telescope foundation to vibrate and, hence, result in blurred photographs taken through the telescopes.)

Table 2.2-1 presents a summary of the various physical factors describing the operational complaint data compiled as a result of the inquiries to FHWA, state and municipal agencies. The following conclusions are drawn from the data summarized in Table 2.2-1.

1) 88% of the cases resulted from action taken by individuals.

2) 90% of the cases related to private residences
4% of the cases related to rental property
6% of the cases related to commercial property

3) 82% of the cases placed source and receiver within 400 feet (122m) of each other

4) 63% of the cases alleged vibration annoyance only
19% of the cases alleged building damage only (annoyance not mentioned)
2% of the cases alleged noise resulting from vibration only
4% of the cases alleged combined vibration annoyance and building damage
6% of the cases alleged combined building damage and noise resulting from vibration
2% of the cases alleged combined vibration annoyance, building damage, and noise resulting from vibration

5) 47% of the cases identified only heavy vehicles as causing perceptible vibrations

TABLE 2.2-1

SUMMARY OF COMPLAINT DATA FOR TRAFFIC-INDUCED VIBRATIONS

COMPLAINT CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
INDIVIDUAL ACTION	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	O	O	O	O		O	O	O	O		O		O	O	O	O	O	O		O	O
GROUP ACTION																O																			O					O									O		
PRIVATE RESIDENCE	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	O		O	O	O		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	
RENTAL PROPERTY																																																O			O
COMMERCIAL PROPERTY																							O				⊕				O																				
WITHIN 400' OF SOURCE	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O	O	O	O	O	O	O	O	O		O	O		O	O	O	O	O	O	O				O			O
BEYOND 400' OF SOURCE																																																			
ANNOYANCE	O	O	O	O				O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O								O	O	O	O	O	O	O	O	O	O	O	O				O			
BUILDING DAMAGE					O											O										O	O	O	O	O	O				O	O									O	O	O		O	O	O
NOISE MENTIONED																												O	O		O	O			O																
HEAVY VEHICLES ONLY				O		O	O	O					O							O				O	O			⦶	O	O	O	O	O	O		O	O		O	O	O	O	O	O	O						O	O
ALL TRAFFIC														O											O									O			O						O		O	O	O	O	O		
TRAFFIC SPEED A FACTOR																											O																			O	O		O		
DAMAGED ROAD SURFACE	O				O								O	O								O								O		O			O	O					O			O			O				O
SMOOTH ROAD SURFACE		O		O		O		O	O	O		O	O	O	O	O	O	O			O	O	O	O				O			O		O	O			O			O					O	O		O	O		
UNEVEN ROAD SURFACE			O				O				O								O	O					O	O	O		O									O	O			O	O							O	
SITE LAYOUT AVAILABLE					O	O												O		O	O					O	O	O	O	O	O	O	O			O															
SOIL DATA AVAILABLE																O														O		O							O	O				O				O	O		
VIBRATION DATA AVAILABLE																										O	O	O	O	O	O	O	O									O			O						
ROAD MAINTENANCE PERFORMED	O	O		O	O	O						O	O	O	O	O	O	O	O	O	O	O	O	O				O		O		O		O	O	O	O	O		O	O			O	O		O				O
OTHER CORRECTIVE MEASURES																																	O													O					
NO ACTION TAKEN																										O	O	O	O		O								O			O						O	O		
LITIGATION INVOLVED																									O																	O									
CLAIMS PAID																																																			
WINTER								O						O	O	O	O																												O	O	O	O		O	O
SPRING									O									O	O	O	O															O		O		O									O		
SUMMER	O	O								O	O											O				O					O	O	O				O				O	O	O	O							
FALL			O	O	O	O	⦶					O	O										O	O	O					O					O				O												

REMARKS

⊕ CHURCH

⦶ PAVEMENT REMOVAL EQUIPMENT

20% of the cases identified all traffic as causing perceptible vibrations
8% indicated that vehicle speed was a factor

6) 26% of the cases identified specific damage to the road surface as causing perceptible vibrations
59% of the cases identified rough road surfaces as causing perceptible vibrations

7) 63% of the cases were passively alleviated by resurfacing the roadway and/or performing maintenance
40% of the cases were passively alleviated by lowering the speed limit or decreasing allowable load limits on the roadway
18% of the cases resulted in no action by the delegated public agency

8) 2% of the cases resulted in litigation with results unknown at this time.

9) All cases were uniformly distributed over the four seasons of the year.

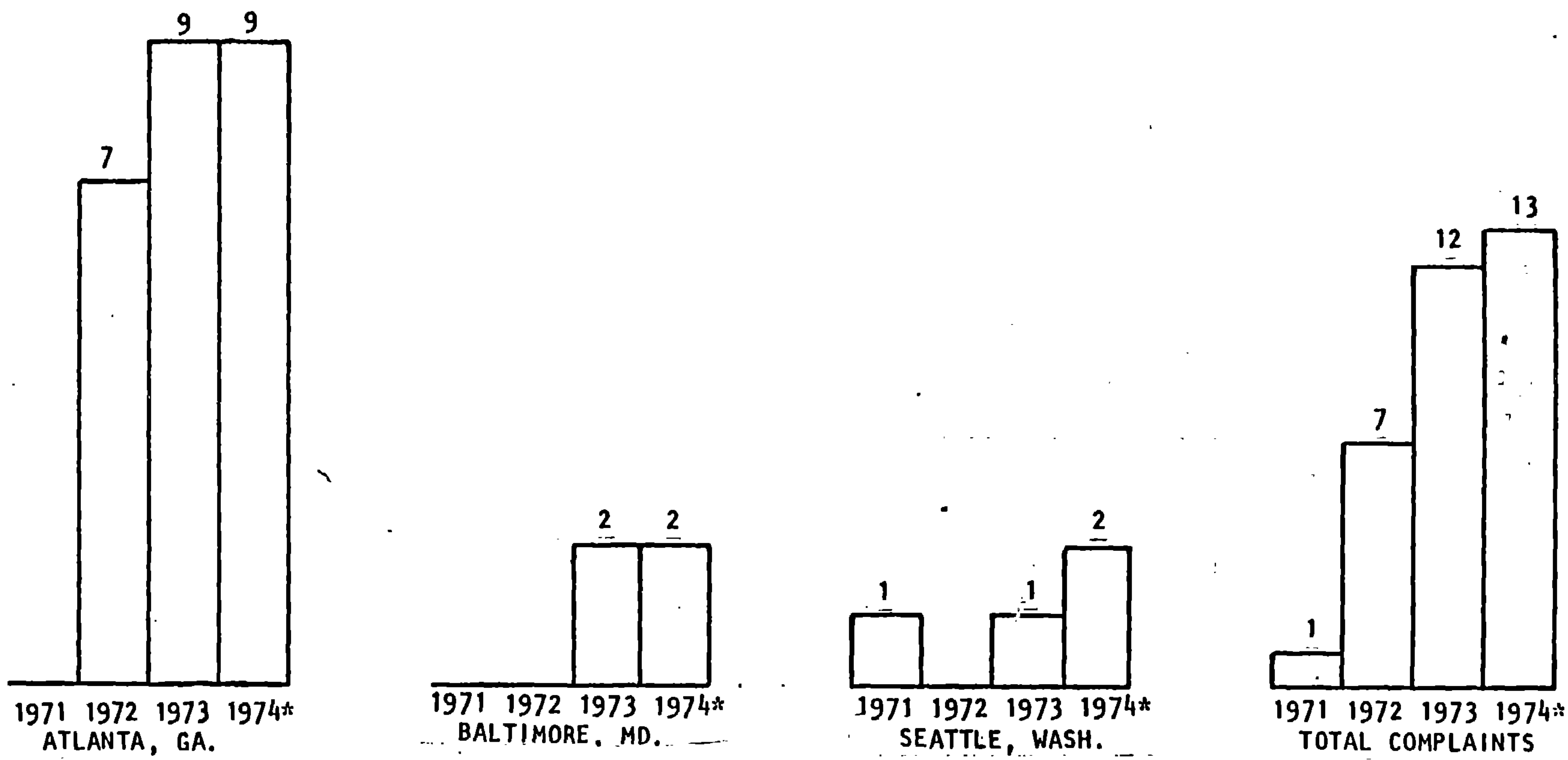
The compilation of complaint data also indicated that the occurrence of complaints related to traffic-induced vibration is increasing from year to year. Since the complaint data has been compiled from existing public records and since the complaintants usually make themselves well-known to local officials through telephone calls and correspondence, it is reasonable to assume that the complaint data is complete. Figure 2.2-1 was prepared to indicate the number of complaints received by year for three of the municipalities contacted.

The following conclusions have been developed as a result of the complaint data evaluation conducted under Task B:

- Highway planners and designers can expect to be faced with resolving traffic-induced vibration as an environmental factor in conjunction with air pollution, noise, and other potential adverse impacts associated with highway construction and operation.

- Traffic-induced vibration is essentially an urban problem that can occur generally within 400 feet(122m) of a highway or street carrying heavy vehicles at moderate speeds. (Every municipal agency contacted had experienced traffic-induced vibration problems.)

- Public complaints generally arise from either annoyance at feeling a structure vibrate and/or observing some form of building damage that is alleged to result from traffic moving over a highway. Highway agencies can expect very persistent action by the public until the agency alleviates and/or resolves the situation.



* COMPLAINTS RECORDED THROUGH OCTOBER 31, 1974

FIGURE 2.2-1 TRAFFIC-INDUCED VIBRATION COMPLAINTS BY YEAR FOR THREE METROPOLITAN AREAS

- The frequency of complaints related to highway-induced vibration appears to be increasing about 10% to 20% per year.

- Highway agencies, public works departments, transit authorities, and other affected public agencies are generally unaware of the data available to assist in resolving these problems and, as a result, are extremely sensitive when approaching complaints related to traffic-induced vibration.

The sensitive approach taken by public agencies when dealing with traffic-induced vibration is undoubtedly due in part to the apparent complexities in describing quantitatively (on a technical basis) the relationship between the source (traffic) and the receiver (building and occupants) and the potential legal situation if annoyance and property damage are alleged.

In addition to locating, compiling, and assessing complaint data related to traffic-induced vibration, the effort in Task B also included an evaluation of the legal codes and literature in the United States to determine the foundations and precedents upon which litigation related to traffic-induced vibration has been based. The detailed results of this task are presented in Appendix III. A summary of these results are presented here.

Environmental vibration, including highway vibration, has not been the subject of much legislative activity in the United States. The Noise Control Act of 1972 focuses on measurable (acoustic) sound and is not concerned with perceptible vibration or effects of vibration separable from sound. This differs from the approach taken by common law courts in the United States which have always been willing to recognize vibration and noise as differing aspects of a common nuisance activity.

Federal statutes phrased in general terms which codify a governmental duty to protect environmental quality and to guard against adverse environmental effects will allow the complaintant, in the appropriate case, legal redress since the courts recognize vibration as an environmental insult. Although no vibration cases have, at this time, been decided under these statutes, the standard of environmental quality provided for would require appropriate safeguards to be implemented by federal officials during the construction and maintenance of a project. Pertinent federal statutes are:

- National Environmental Policy Act (42 U.S.C. 4321, paragraphs 101 and 102)

- Federal Highway Act (23 U.S.C., 109h)

- FHWA: 23 Code of Federal Regulations, Appendix A, Environmental Impact Statements, Paragraph 4

- Historic Preservation (16 U.S.C., 470(f))

- FHWA: 23 Code of Federal Regulations, Appendix A, Procedures for Historic Preservation

- FHWA: 23 Code of Federal Regulations, Part 772 (Regulations promulgated pursuant to the Noise Control Act)

State statutes regulating vibration have recently been enacted (1974 legislative session: Connecticut, Kentucky, and Maryland) based upon the Council of State Government's suggested State Noise Control Act. This model regulation does not attempt to regulate vibration specifically but expands the definition of noise to include vibration. This type of statute could be applied to traffic-induced vibration, but since the statutes are new, no litigation or enforcement activity has resulted.

Municipal ordinances regulating vibration generally form a part of the zoning codes and resemble classic nuisance ordinances. Since zoning codes are generally concerned with stationary sources of noise, vibration, fumes, smoke, etc., it is problematical that these ordinances are broad enough, in their present form, to deal with traffic-induced vibration. However, since many cities have passed noise ordinances relative to moving sources, it is conceivable that traffic-induced vibration could be encompassed by municipal codes. Whereas some municipal ordinances are subjective in respect to vibration intensities and duration, other municipal codes are quite specific in their regulations as indicated in Table 2.2-2.

As noted in Table 2.2-2, some zoning codes are rather technically sophisticated (Peoria, Columbus, and Tucson) whereas the Chicago and Denver codes rely totally upon the subjective response of individuals and the level of human vibration perception.

Since human perception and response to vibration represents a very significant factor in anticipating complaints, the assessment of complaints also included a compilation and evaluation of the quantitative description of human vibration perception and psychological factors that possibly influence the variability of the levels of human perception and response to vibration. The details of the results of this sub-task are presented in Appendix IV, Human Response to Building Vibration. A discussion of the interrelationships between the quantitative measure of human vibration perception and other aspects of the traffic-induced vibration problem are discussed in the following section.

There has been no attempt, either nationally or locally, to draft a comprehensive statutory scheme to regulate vibration such as has been the case with noise. Whereas the National Environmental Policy Act could theoretically serve as a basis for plaintiff's relief in future litigation, the control of excessive environmental vibration is currently approached by the plaintiff using the traditional, but limited and rather ineffective, theories of nuisance and inverse condemnation.

Common law courts have recognized excessive vibration as an insult which may be redressed using a number of traditional legal remedies such as nuisance or inverse condemnation. As a result, a survey of adjudicated cases arising from vibration was conducted. This survey covered both non-highway cases and highway-related vibration cases since vibration, if considered excessive, very well may be viewed by the courts as only various aspects of a common offense.

TABLE 2.2-2

EXAMPLE MUNICIPAL ZONING CODES REGULATING VIBRATION

MUNICIPALITY	QUANTITATIVE MEASURE OF VIBRATION
Chicago, Ill.	Vibration must not be perceptible (without instruments) at lot line.
Peoria, Ill.	Three component ground velocity measurements specified along a lot line. Computation of velocity from displacement measurements allowed. Continuous and impulse vibration defined.
Columbus, Ohio	Table of distance versus allowable pounds of explosive for blasting operations. Ground displacement amplitude spectra defined.
Denver, Colo.	Vibration must not be perceptible (without instruments) at lot line.
Tucson, Ariz.	Humanly perceptible vibration beyond a lot line for three minutes or more in any one hour between 7:00 AM to 7:00 PM or for thirty seconds or more in any one hour between 7:00 PM to 7:00 AM is not allowed.

Details of the various adjudicated cases are presented in Appendix III where the classification of these cases is made as follows:

- The Constitutional Requirement of Compensation
- Tangible versus Intangible Damages
- Highway Construction
- Highway Operation
- Inadequacy of Nuisance Law
- Private Party Defendants
- Inverse Condemnation
- Severance Damages
- Special Damages
- Special Plantiffs
- Procedure

From this effort, it has been concluded that a property owner proving that cracked walls, broken windows, or other forms of tangible injury have resulted from highway operations will receive damage awards by the courts. If the property owner seeks damages for annoyance only, it is necessary to examine the state law, but if the property owner has been awarded severance damages, such as partial land acquisition for highway right-of-way, it is much more likely that additional damages will be awarded as compared to a property owner whose land is simply adjacent to the highway. Special damages that have not been suffered by the community at large have been successfully claimed by such plaintiffs as hospitals, schools, and churches.

Table 2.2-3 is presented as a result of the Task B effort to indicate an assessment of litigation related to traffic-induced vibration (See Appendix II, Table AII-4). It is possibly significant to note that seven of the eight cases reported for the time period 1970 to 1973 were ruled in favor of the plaintiff. Three cases alleged building damage (38%), and five cases alleged annoyance (62%), six cases identified heavy vehicles only as the source (75%), and two cases identified all traffic as the source (25%). Considering the sample size this data correlates reasonably well with the analysis of complaint data presented in Section 2.2.

TABLE 2.3-3

SUMMARY OF ADJUDICATED CASES RESULTING FROM HIGHWAY RELATED VIBRATION PROBLEMS 1963-1972

Complaint Case No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Individual Action		x					x	x	x	x	x	x	x	x			x	x	
Board or Comm. Action	x		x	x	x	x									x	x			x
Private Property		x				x	x	x	x	x	x	x	x	x					x
Public Property	x		x	x	x										x	x		x	
Commercial Property																	x		
Source Within 400'	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Source Beyond 400'																			
Building Damage		x	x			x		x			x		x		x				x
Annoyance	x			x	x		x		x	x		x		x		x	x	x	
Noise Mentioned	x		x	x	x	x	x		x	x		x		x	x	x	x	x	x
Heavy Vehicles/Machinery		x	x	x			x	x	x	x	x		x	x	x	x	x		x
All Traffic	x				x	x						x						x	
For Plaintiff	x*		x						x			x	x+		x	x	x	x	x
Against Plaintiff		x		x	x	x	x	x		x	x			x					
Year	1963	1964	1965	1965	1966	1966	1968	1968	1968	1969	1969	1970	1970	1970	1971	1971	1971	1972	1972

Remarks * The court awarded $9,210.00 to compensate for diminution of value.

+ The court awarded $37,150.00 for damages.

3.0 ENGINEERING ANALYSIS

The engineering analysis of traffic-induced vibration comprised the major effort of the project. The objective of the analysis was the development of a quantative methodology to determine the impact of traffic-induced vibration. The literature review (Appendix I) indicated that a quantative methodology (or even a general approach to the problem) had not been established. The complaint assessment (Appendix II) and legal review (Appendix III) indicated that the problem of traffic-induced vibration could occur. The availability of accepted criteria for evaluating human response to vibration was not clearly established. With this available information, the engineering analysis of the traffic-induced vibration problem proceeded.

3.1 Characterization of Traffic-Induced Vibration

The characterization of highway traffic-induced vibration is analogous to the characterization of highway traffic noise. Both traffic noise and traffic vibration comprise a source-path-receiver scenario. For highway traffic noise, the source is defined by the traffic flow and the highway alignment relative to the receiver. For highway traffic-induced vibrations, the source is defined by the traffic flow, the highway surface roughness, details of the pavement/subgrade structure, and the highway alignment relative to the receiver. For both highway traffic noise and traffic-induced vibration, the more significant traffic flow parameters are vehicle speed and weight with increasing speed and weight resulting in higher levels of both noise and vibration.

Away from the highway alignment, both traffic noise and vibration decrease in level with increasing distance. Generally, traffic noise is not an environmental consideration beyond 1000 feet (305 metres) from a roadway. Generally, traffic-induced vibration is not an environmental consideration beyond 200 to 300 feet (61 to 90 metres) from the roadway.

Considering the receiver to be an occupant or an activity in a building adjacent to a roadway, the main difference between traffic noise and vibration becomes evident. Building structure attenuates or decreases the amplitude of traffic noise. Highway traffic-induced vibration, as received at the building foundation, may cause the building structure to amplify the vibration. Depending upon the amplification, the floor or wall vibration inside a building may be perceptable to an occupant. Whereas, traffic noise may be perceptable but not annoying to a building occupant, the perception of traffic-induced vibration may result in complaints, concerted public action, and litigation.

Figure 3.1-1 presents an outline of the traffic-induced vibration problem. The main objective of the present study was to quantify the impact of traffic-induced vibrations in terms familiar to highway design engineers. The concepts and techniques used to quantify traffic-induced vibration are identical to those used in traffic noise analyses. Highway design engineers should encounter little difficulty in utilizing the results of the study.

Figure 3.1-2 presents a graphic comparison of the relationship between highway traffic noise and highway-traffic induced vibration.

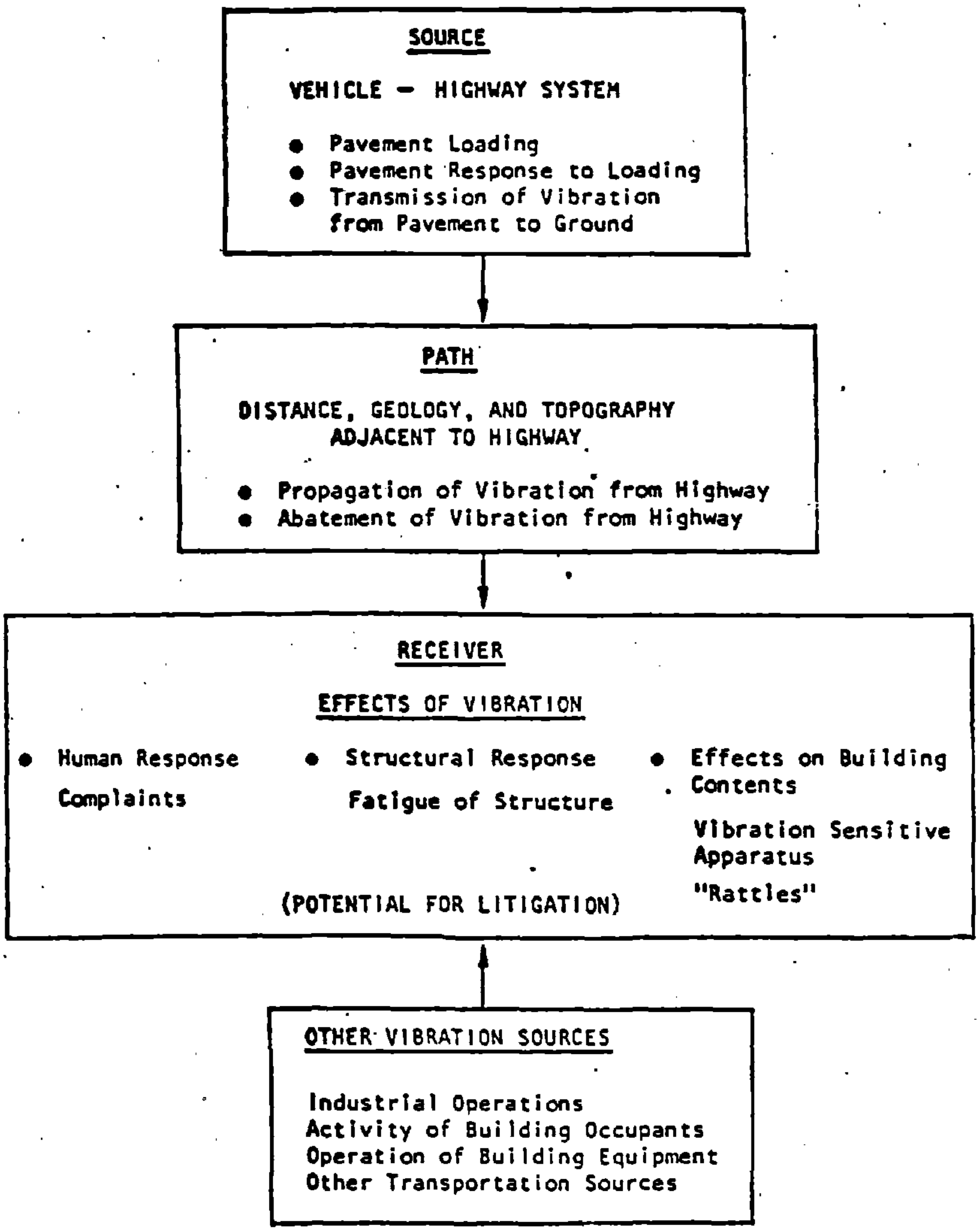


FIGURE 3.1-1. TRAFFIC-INDUCED VIBRATIONS: OUTLINE OF PROBLEM

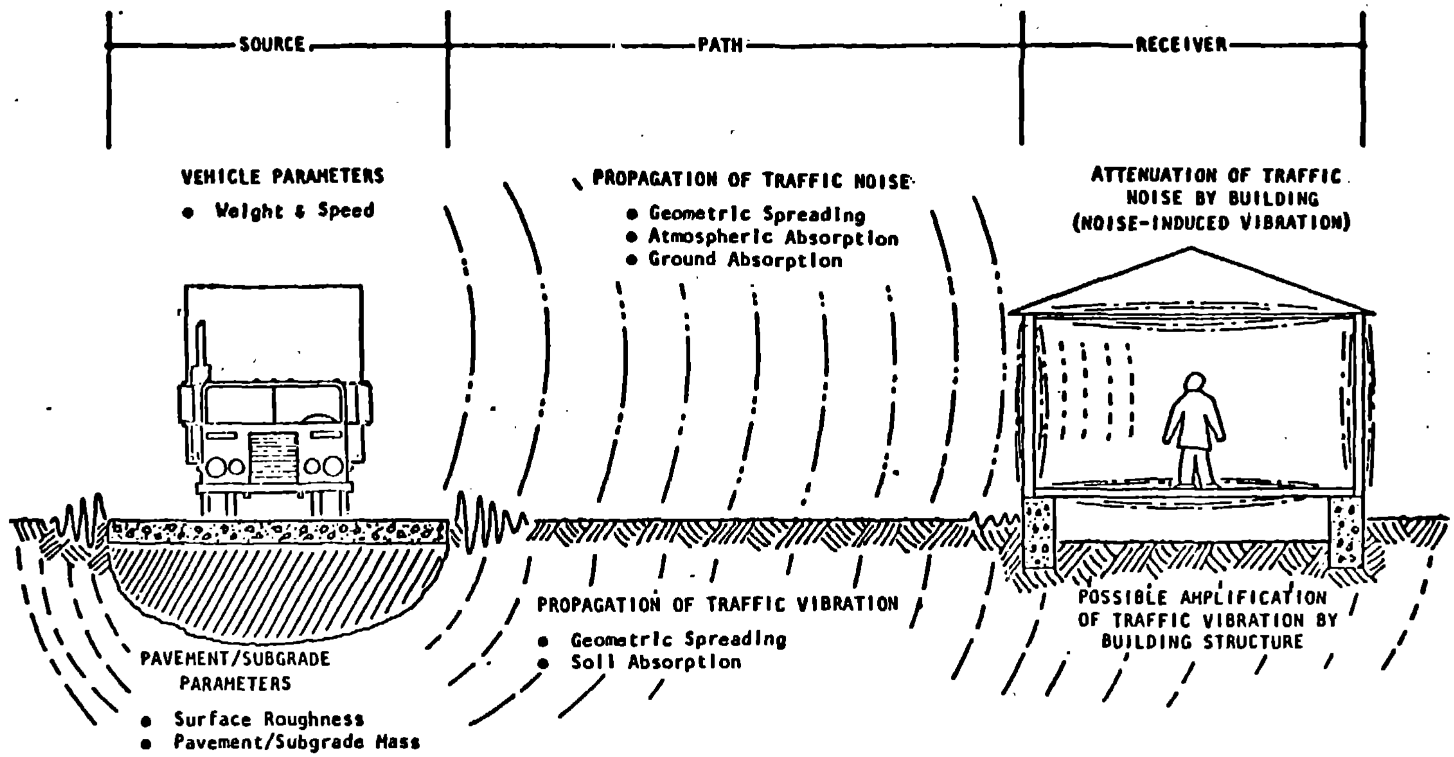


FIGURE 3.1-2. SOURCE-PATH-RECEIVER SCENARIO FOR TRAFFIC NOISE AND VIBRATION

3.2 Description of Traffic Induced-Vibration

3.2.1 Sound Level and Vibration Level

The decibel (dB) is a convenient measure used for both traffic noise and traffic-induced vibration. The concept of an equivalent level, expressed in dB, may be used to characterize both traffic noise and traffic-induced vibration.

For atmospheric noise, the physical quantity that is conveniently measured for amplitude description is acoustic pressure. For vibration, the physical quantities that are conveniently measured for amplitude description are displacement, velocity, or acceleration. If the frequency of the vibration is known, displacement, velocity and acceleration are all related.

Acceleration was used as the vibration amplitude measure in this study. The acceleration levels, expressed in dB, are referenced in this study to an acceleration of "1g" or 9.807 metres/(second)^2. Peak acceleration amplitudes associated with traffic-induced vibration are on the order of 0.001g to 0.030g. Hence, peak acceleration levels are on the order of -60 dB (re: 1g) to -30 dB (re: 1g). Using this convention, acceleration levels cannot be confused with noise levels from traffic.

3.2.2 Criteria for the Evaluation of Vibration Impact

Traffic noise is well defined with respect to both a level metric and associated criteria. Traffic noise levels are expressed in terms of the A-Weighted sound level. The A-Weighted sound level is a single number based upon frequency weighting of the sound pressure. Accepted values of the A-Weighted sound level have been developed over the past several years that related sound level to effects of noise on people and structures.

Environmental vibration is not so well defined as environmental noise with respect to either a level metric or the associated criteria. Standardized frequency weighting for vibration, such as the A-Weighted sound level for noise, is not available. Standardization of frequency weighting for acceleration does appear to be possible in the near future (3).

Criteria relating vibration amplitude to effects on people and structures is available. Table 3.2-1 presents a criteria description and related acceleration levels. For comparison, sound levels corresponding to the criteria are also presented.

The listing in Table 3.2-1 is important in quantifying highway-traffic-induced vibration.

TABLE 3.2-1

COMPARISON OF NOISE AND VIBRATION LEVELS AND REPRESENTATIVE CRITERIA

NOISE Sound Level dB (re. 2×10^{-5} N/m^2)	Criteria Description	VIBRATION Acceleration Level, dB (re. $1g_{rms} = 9.8m/s^2$) (Approximate)
0	Threshold of Perception	-65
55-65	Annoying	-60
90	Extremely Annoying	-45
120	Threshold of Structural Damage*	-35
130	Structural Damage of Concern*	-25
>140	Structural Damage Highly Probable*	>-15

* The nature of structural damage is generally a fatigue effect.
That is, cracks and damage slowly progress over a period of time and may not be directly related to a single event or source.

The levels presented in Table 3.2-1 indicate that from perception to a high probability of structural damage, acceleration levels cover a 50 dB range and sound levels cover a 140 dB range. For both noise and vibration, the threshold for structural damage is a higher level than the level for extreme annoyance. For noise, the range between extreme annoyance and structural damage threshold is approximately 30 dB (a factor of 32 in pressure). For vibration, this range is approximately 10 dB (a factor of 3.2 in acceleration). For noise, the range between perception and annoyance is approximately 60 dB (a factor of one thousand in pressure). For vibration, the range between perception and annoyance is about 5 dB (a factor of 1.8 in acceleration).

Hence, for evaluating the effects of environmental vibration, the significance of a change in accleration level is much greater than an identical change in sound level. Whereas, a 1 dB change in sound level either in measurement or prediction is generally considered insignificant, 1 dB change in vibration leve may be very significant.

For both noise and vibration, the association of criteria with levels are dependent upon the frequency content of the noise or vibration signal. Figure 3.2-1 presents criteria curves (acceleration level versus frequency) for the evaluation of traffic-induced vibration. Figure 3.2-2 presents criteria relating vibration amplitude to the number of occurrences per day. These criteria are from Reference 3.

3.3 Parameters Governing Traffic-Induced Vibration

The major effort and primary result of the study was to identify the significant parameters describing traffic-induced vibration. These parameters and their interrelationship are described below for random pavement roughness. Discrete pavement roughness, such as bump, is discussed separately.

3.3.1 Traffic Parameters

Gross vehicle weight and vehicle speed are the primary traffic parameters affecting ground vibration from highway operations. Ground vibration increases approximately 3 dB for each doubling of gross vehicle weight. That is, a vehicle weighting 20,000 pounds (44092 kgf)* would be expected to generate 3 dB more ground vibration that a vehicle weighing 10,000 pounds (22046 kgf). The effect of vehicle speed depends on the pavement roughness. Increasing vehicle speed increases ground vibration within the limits of 3 dB to 6 dB per doubling of speed. An appropriate design value for vehicle speed is 5.2 dB per doubling speed. That is, a vehicle traveling 60 miles per hour (97 km/h) would be expected to generate ground vibration 5.2 dB greater than the same vehicle traveling 30 miles per hour (48 km/h).

Complaints related to traffic-induced vibration appear to be dependent upon the number of occurrences or intrusions perceived during a 24 hour period. Criteria are presented in Figure 3.2-2 relating number of occurrences to vibration level.

*kgf is kilograms force or Newtons

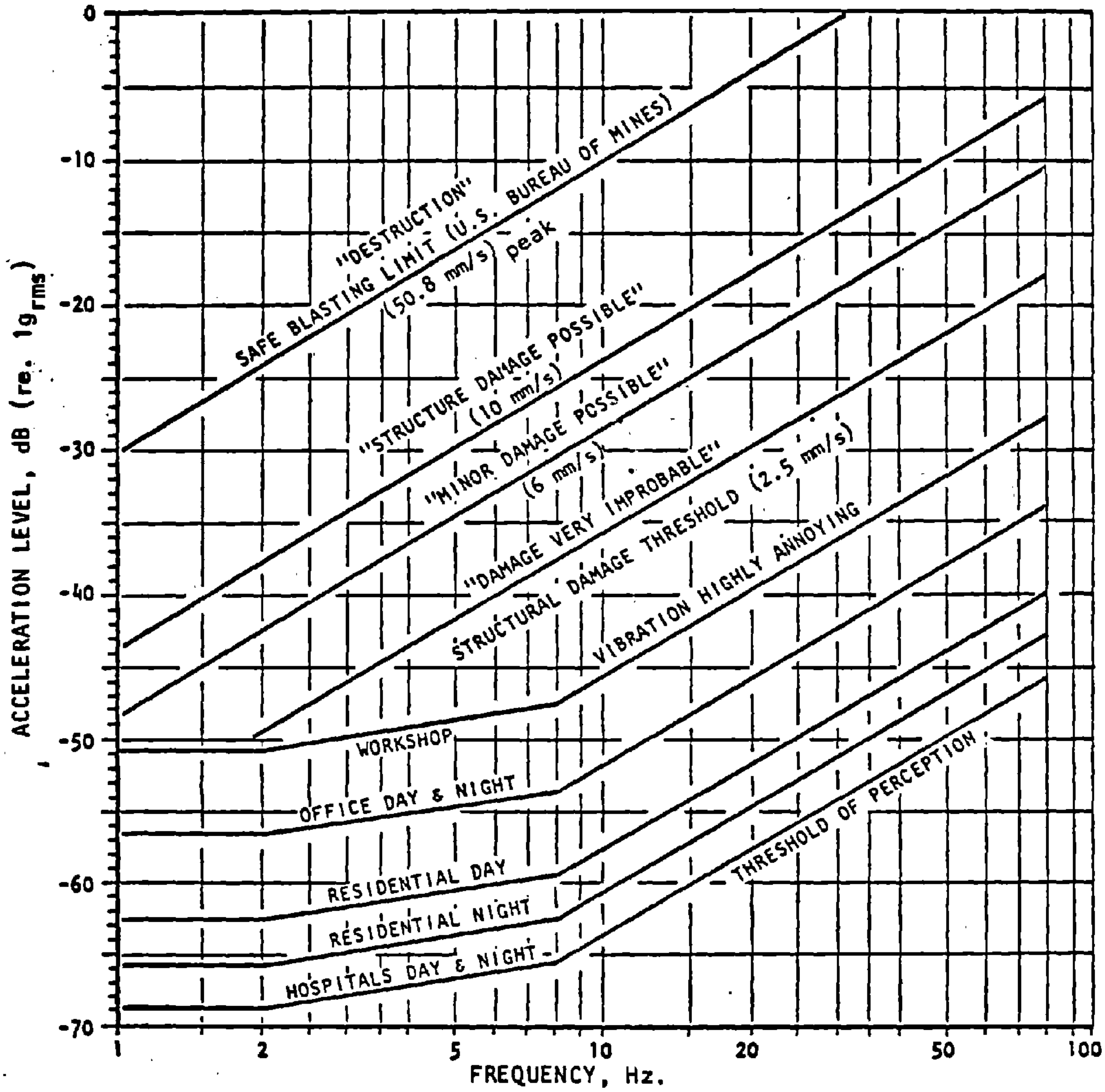


FIGURE 3.2-1. CRITERIA CURVES FOR ENVIRONMENTAL VIBRATION: ACCELERATION LEVEL VERSUS FREQUENCY

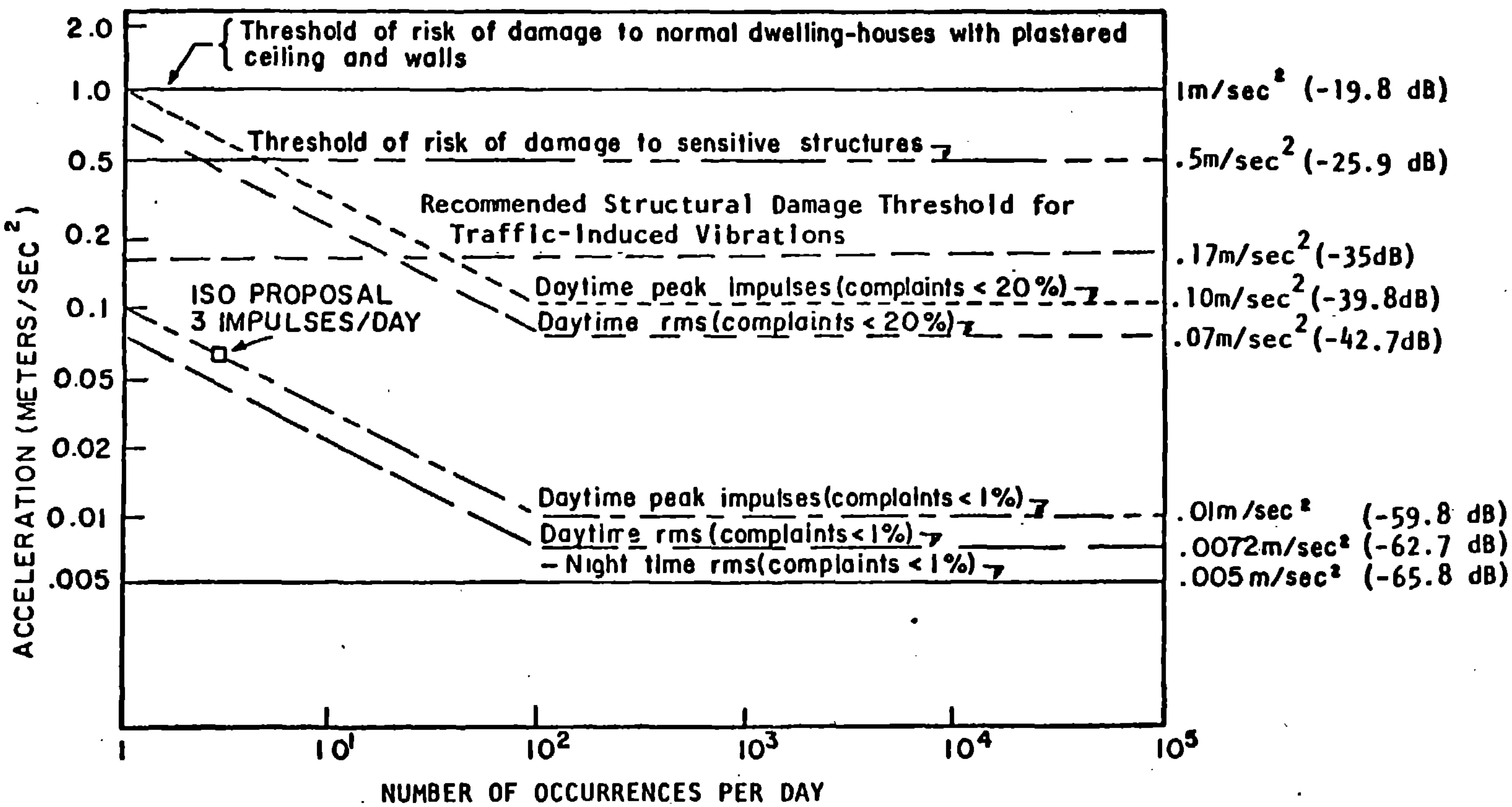


FIGURE 3.2-2. VIBRATION CRITERIA FOR BUILDING INTERIORS IN RESIDENTIAL AREAS

Figure 3.3-1 presents a nomograph for estimating the vibration emission of vehicles. The use of this nomograph is described in Reference 1.

3.3.2 Pavement/Subgrade Parameters

Pavement surface roughness is the primary factor affecting ground vibration generated by highway traffic. Technical details concerning the description of random surface roughenss are presented in Appendix V. As an approximation, ground vibration increases 4.2 dB with each unit decrease in the Present Serviceability Rating (PSR) index. That is, a decrease in the PSR index from 4.5 to 2.5 would be expected to increase ground vibration by approximately 8.3 dB. This result is presented in Figure 3.3-2.

A secondary parameter is the mass of the pavement/subgrade system. Increasing the mass of the pavement/subgrade system decreases the amplitude of ground vibration generated by traffic. This decrease involves technical details and is described in Appendix V. From a practical standpoint, the effect of pavement/subgrade mass appears to be controllable only by achieving good compaction of the subgrade/ base material.

3.3.3 Pavement Loading

A secondary finding of the study, effects of vehicle-pavement interaction and resulting pavement loading were obtained. These technical details are described in Appendix V. Since dynamic force is proportional to acceleration, the comments in Sections 3.3.1 through 3.3.2 regarding changes in acceleration level are analogous to pavement dynamic loading.

The above discussion concerning traffic and pavement/subgrade parameters relates only to random surface roughenss. Discrete pavement surface irregularities such as potholes, expansion joints, grates, "rumble strips", etc. require special consideration.

Figure 3.3-3 presents a design nomograph to estimate the peak impulse pavement loading resulting from a loaded tire striking a bump in the pavement. The development of this nomograph is described in Appendix V. This result may be used to scale "impact factor" data used by pavement design engineers. It is believed that this result is new.

3.3.4 Pavement/Subgrade Response to Loading

With a knowledge of the pavement/loading, it is necessary to estimate the response of the pavement/subgrade system to the loading. The literature review indicated that models of pavement/subgrade systems currently used for pavement design were inadequate to describe the traffic-induced vibration problem. Hence, it was necessary to develop an appropriate model for this purpose.

(See Reference 1 for Example of Use).

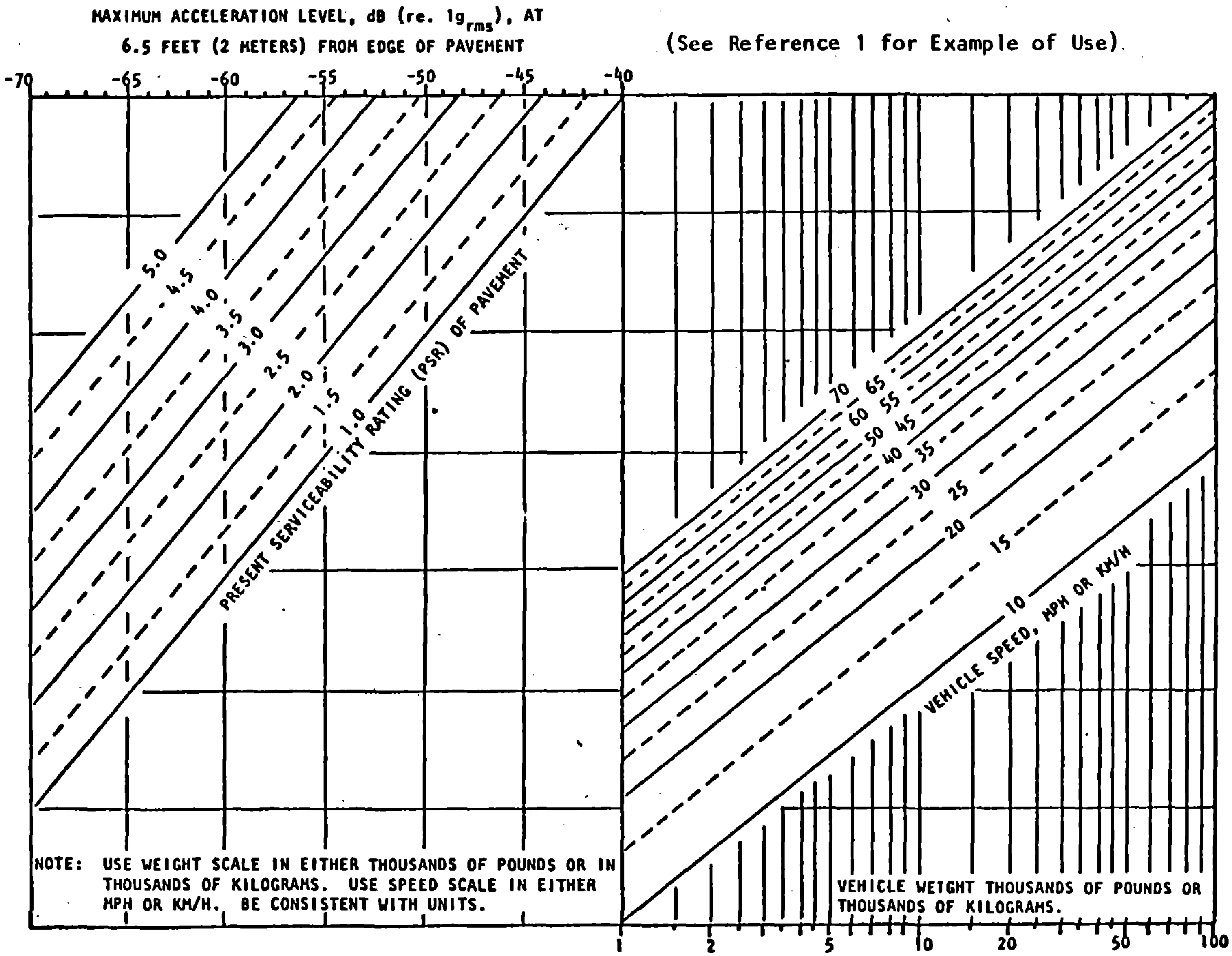


FIGURE 3.3-1. DESIGN NOMOGRAPH FOR ESTIMATING THE VIBRATION REFERENCE EMISSION LEVEL

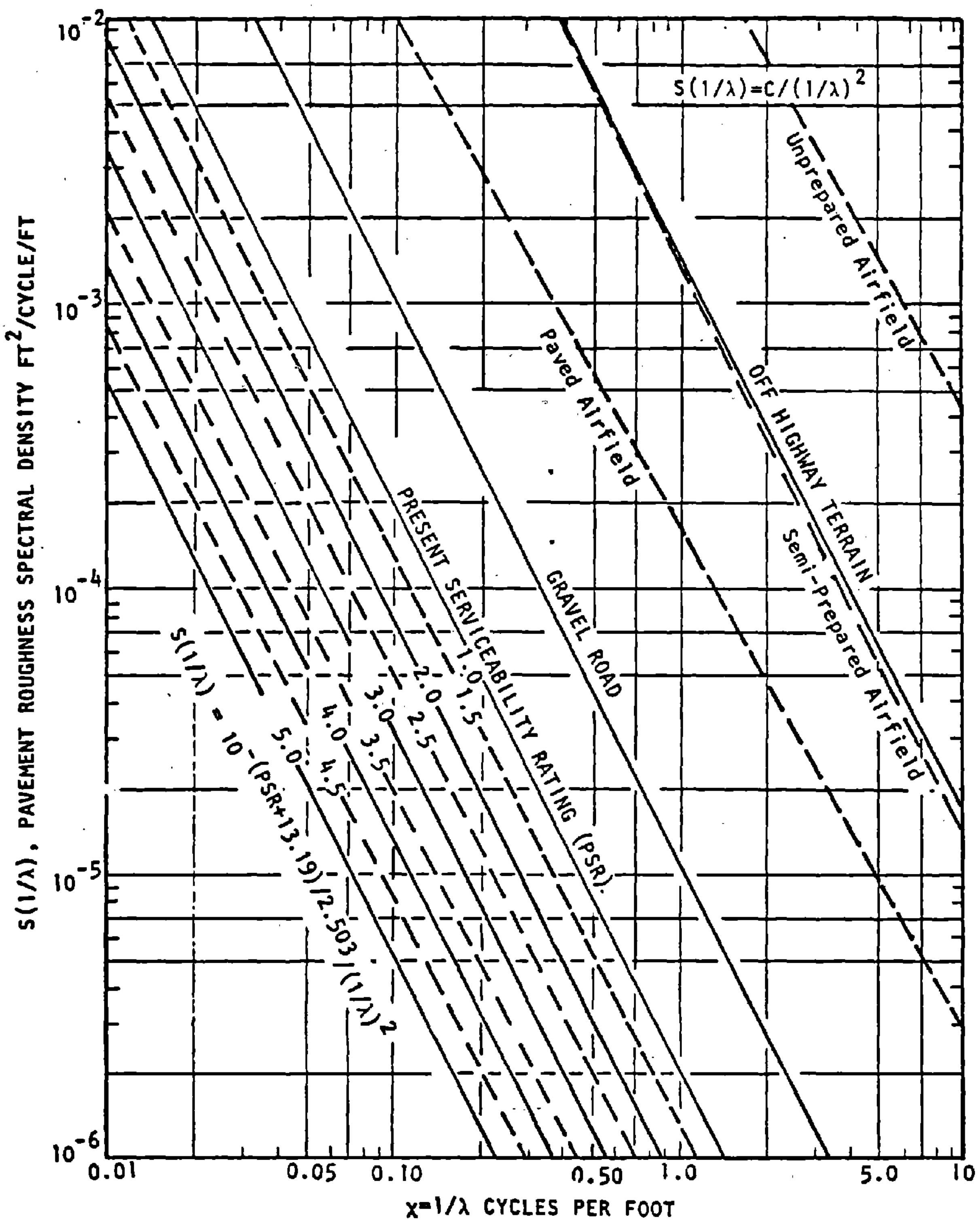


FIGURE 3.3-2. PAVEMENT ROUGHNESS POWER SPECTRAL DENSITY FUNCTIONS

Considerable effort was devoted to developing and refining a dynamic model of the pavement/subgrade system. The model in this study is an elastic slab resting on a single-layer elastic subgrade. The development of this model is described in Appendix V.

By considering a range of parameters describing the pavement/subgrade vibration characteristics, the fundamental vibration mode is the dominant dynamic characteristic. The model simulates both radiation stiffness and damping of the pavement/subgrade with the surrounding parent soil system. The data required to use this model are common engineering parameters used in pavement design.

3.3.5 Propagation Parameters

The propagation of traffic-induced vibration away from the highway depends upon the soil characteristics and the soil conditions between the pavement and the receiver. Ground vibration from highway traffic decreases with distance away from the highway much more rapidly than traffic noise. Technical details are presented in Appendix V and Reference 1 and 2. It appears that distances beyond 200 to 300 feet (61 to 91 metres) from a highway need not be considered for adverse impact from traffic-induced vibration.

3.3.6 Building Parameters

Ground vibration received at a building foundation may cause an amplification of vibration on the interior of the building. The degree of amplification depends upon details of the building construction. Floor vibration generally increases with increasing building storeys. For design use, the building amplification appears to be from -5 dB to +10 dB for ground level floors and -5 dB to +15 dB for second floors. Levels of traffic-induced vibration generated in buildings that may result in complaints (approximately -65 dB (re: $1g_{rms}$)) are on the order of magnitude of levels generated appliances, etc. Figure 3.3-4 presents a set of "building amplification in curves". The use of these curves in the prediction methodology is described in Reference 1.

3.4 Development of Engineering Guidelines

The quantatative description of traffic-induced vibration requires the evaluation of many parameters. These parameters are interrelated in a rather complex manner. In order to present an evaluation methodology for traffic-induced vibration, engineering design guidelines were developed. These guidelines integrate the various considerations required to evaluate traffic-induced vibration problems. The engineering design guidelines for traffic-induced vibration are reported in Reference 1.

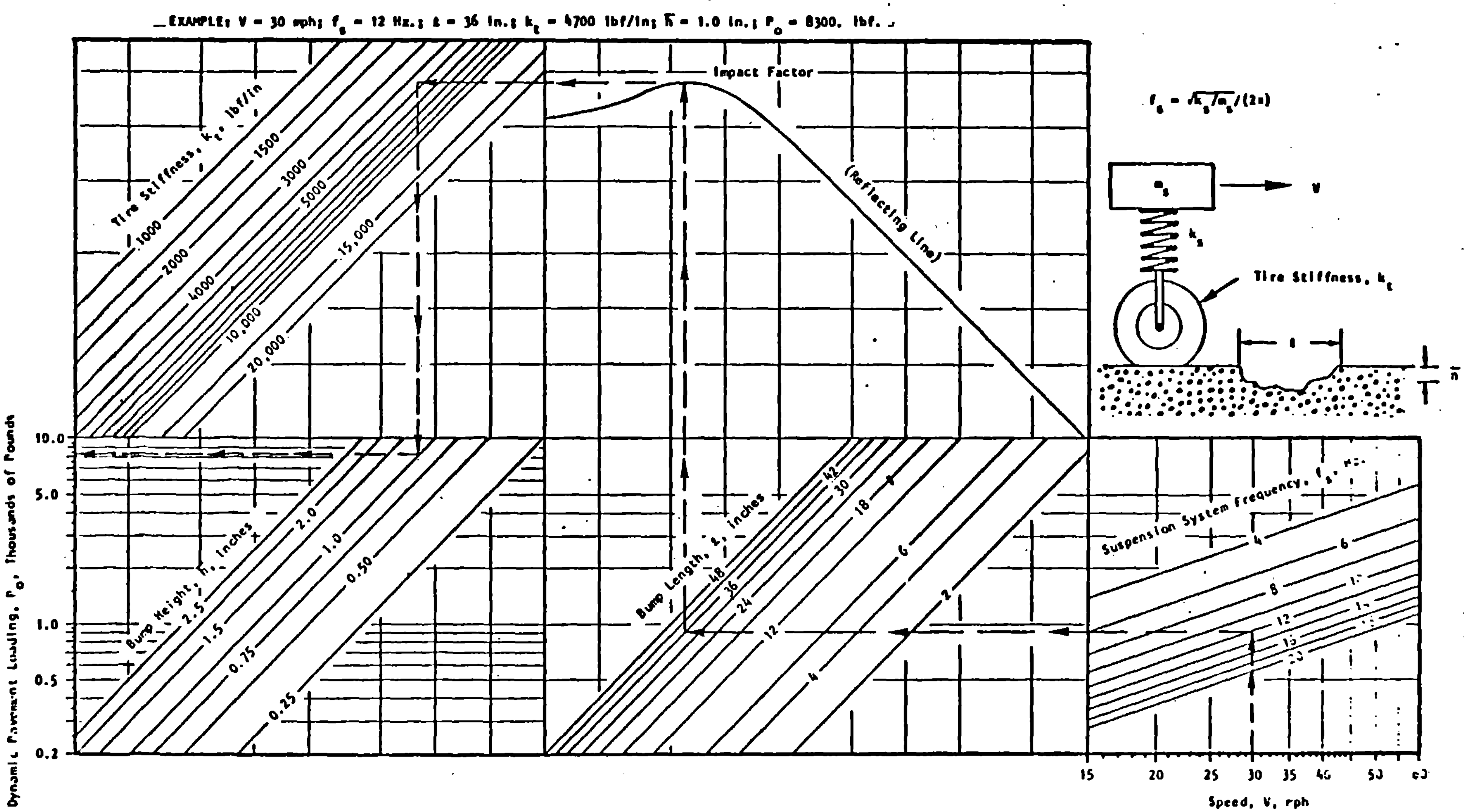


FIGURE 3.3-3. DESIGN NOMOGRAPH FOR PEAK IMPULSE PAVEMENT LOADING

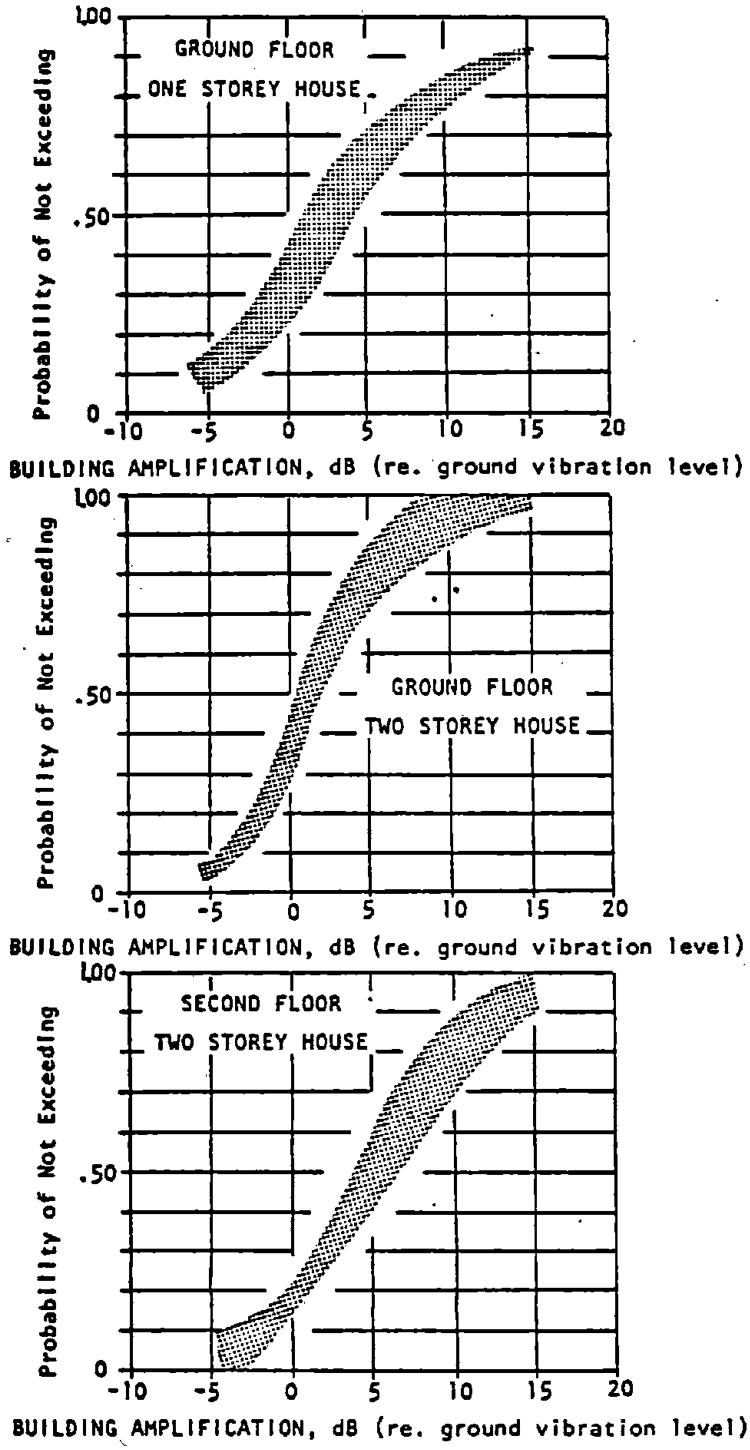


FIGURE 3.3-4. PROBABILITY OF NOT EXCEEDING BUILDING AMPLIFICATION

3.5 Measurement of Traffic-Induced Vibration

Under the Task D effort, field testing was conducted to evaluate and to quantify the problem of traffic-induced vibration. Field measurements were conducted to quantify the problem of traffic-induced vibration. These data are presented in Appendix VI. Based upon these data, the following may be concluded:

- Highway vehicles are point vibration sources even for dense traffic flows
- The vibration annoyance criteria presented in this report and in Reference 1 are adequate to describe the problem, but may be refined in the future.
- The theory and methodology developed in this study are supported by the measured data.
- Due to the complex nature of the traffic-induced vibration problem, field measurements are required to quantify absolutely the degree of potential impact.

4.0 SUMMARY

This report and its appendices contain detailed information on the following aspects of the traffic-induced vibration problem:

APPENDIX I	ANNOTATED BIBLIOGRAPHY (by F. F. Rudder and S. D. Pettyjohn)
APPENDIX II	ASSESSMENT OF COMPLAINT DATA AND ADJUDICATED CASES (by J. R. Ballantine and M. L. MacIntyre)
APPENDIX III	LEGAL PERSPECTIVE OF TRAFFIC-INDUCED VIBRATION (by Prof. J. W. Futrell)
APPENDIX IV	HUMAN RESPONSE TO BUILDING VIBRATION (by Dr. C. L. Holland)
APPENDIX V	ENGINEERING ANALYSIS OF TRAFFIC-INDUCED VIBRATIONS (by F. F. Rudder and Dr. B. Mazanti)
APPENDIX VI	FIELD MEASUREMENTS OF TRAFFIC-INDUCED VIBRATION (by F. F. Rudder, L. V. Mazzarella, and J. D. Pettyjohn).

These appendices provide a detailed basis to assist public officials and engineers in evaluating traffic-induced vibration problems. The appendices support the methodology, recommendations and conclusions of the Reference 1 guidelines for the analysis of traffic-induced vibration.

REFERENCES

1. Rudder, F. F., Jr.: "Engineering Guidelines for the Analysis of Traffic-Induced Vibrations", U. S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-78-166.

2. Tokita, Y. and Oda, A.: "On the Characteristics of Ground Vibration Generated by Traffic", Inter-noise '75, Tohoku University, Sendai 980, Japan, August 27-29, 1975.

3. Anon.: "Guidelines for Preparing Environmental Impact Statements on Noise", National Academy of Sciences, Washington, D. C., 1977.

APPENDIX I
ANNOTATED BIBLIOGRAPHY

The following annotated bibliography represents the results of the first phase of Task A, Literature Review and Evaluation. The literature review encompassed both a computer search using TRIS and efforts in scanning abstracts, locating source material, and reviewing individual papers or reports. The data listed in this annotated bibliography is supplemented by the literature reviewed and listed in Appendix III on law, in Appendix IV on human response to vibration, and Appendix V on Engineering Aspects.

The listing is categorized by topic as follows:

Source Characteristics (Section A-1)
Path Characteristics (Section A-2)
Receiver Characteristics (Section A-3)
Legal Literature (Section A-4)

A complete listing of the classification topics is presented in Table A-1.

TABLE AI-1

LITERATURE REVIEW AND EVALUATION

TOPIC CLASSIFICATION

(Continued)

A.1 SOURCE CHARACTERISTICS

A.1.1 Highway Vibrations

A.1.1.1 Vehicle and Traffic Flow Description

A.1.1.2 Highway Design, Construction, and Maintenance Standards

A.1.2 Environmental Vibrations

A.1.2.1 Sonic Booms

A.1.2.2 Railway Operational Vibrations

A.1.2.3 Subway Operational Vibrations

A.1.2.4 Construction Generated Vibrations

A.1.2.5 Blasting Vibrations

A.1.3 Vibration Standards & Criteria

A.1.3.1 Standards Controlling Highway Vibration

A.1.3.2 Standards Controlling Environmental Vibration

A.1.3.3 Measurement Standards

A.2 PATH CHARACTERISTICS

A.2.1 Geological Survey Techniques

A.2.1.1 Soil Sampling Techniques

A.2.1.2 Soil Testing Techniques

A.2.1.3 Soil Parameters Related to Highway Design

A.2.2 Wave Propagation

A.2.2.1 Analytical Description

A.2.2.2 Experimental Description and Techniques

A.2.2.3 Experimental Data

TABLE AI-1

(Concluded)

A.2.3 Wave Attenuation

A.2.3.1 Analytical Description

A.2.3.2 Experimental Description and Techniques

A.2.3.3 Experimental Data

A.2.4 Countermeasure Techniques

A.2.4.1 Foundation and Footing Design

A.2.4.2 Trench Design

A.2.4.3 Barrier Design

A.2.4.4 Experimental Data

A.3 RECEIVER CHARACTERISTICS

A.3.1 Human Response to Vibration (See Appendix III)

A.3.2 Structural Response

A.3.2.1 Soil-Foundation Coupling

A.3.2.2 Vibration Characteristics of Building Structure

A.3.2.3 Component Mode Vibration

A.3.2.4 Building Design Standards

A.3.2.5 Building Damage Criteria

A.4 LAWS GOVERNING AND LITIGATION ARISING FROM VIBRATION (See Appendix IV)

A.1.1.1 VEHICLE VIBRATIONS AND TRAFFIC FLOW DESCRIPTION

Yasuo Tokita; "Ground Vibrations Generated by Factorie's Machine and Vehicles," Inter-Noise '73, Tech Univ. of Denmark, Copenhagen, Aug. 22-24, 1973, pp. 85-89. Experimental results presented in the form of graphs for factory equipment and vehicles. Results are to be considered in the legislation of vibration criterion in Japan. Table of day/night horizontal/vertical vibration limits presented.

Whiffin, A. C.; Leonard, D. R.; "A Survey of Traffic-Induced Vibrations," Road Res. Lab, Dept. of the Environment, RRL Report LR 418, Crowthorne, Berkshire, 1971. A general comprehensive study of the generation and transmission of vibrations, measurement of these vibrations, comparison with other sources of ground vibration, structural and equipment response, human reaction and correlation of criteria.

Bata, M.; "Effects on Buildings of Vibrations Caused by Traffic," Build. Sci., V6, pp. 221-246, 1971. Analytical analyses for building motion developed by matrix methods or Laplace transforms, results of experimental work presented in form of a probability histogram and tables of basic characteristics of the investigated statistical sets.

House, M. E.; "Traffic-Induced Vibrations in Buildings," J. of the Instit. of Hwy. Engrs., The Highway Engrs., V20, N2, Feb. '73, p. 6-16. General discussion of excitation forces, pavement/ground response, propagation through soils, foundation and building response, detection and damage criteria and life reduction in buildings. Figures on ground vibration reduction with distance, magnification of vibes in structures, subjective response to vibrations, and life reduction in houses.

Sutherland, H. B.; "A Study of the Vibrations Produced in Structures by Heavy Vehicles," Highway Res. Board Proceedings of the 30th Annual Meeting, 1950. Experimental results. Figures show how various factors affect vibrations. Factors are: 1) weight of vehicle, 2) speed of vehicle, 3) braking and acceleration characteristics, 4) condition of road surface, 5) thickness of road bed, 6) distance of vehicle from structure, and 7) nature of soil underlying roadway.

Trott, J. J.; Whiffin, A. C.; "Measurements of the Axle-Loads of Moving Vehicles on Trunk Roads," Roads & Road Constr., V43, pp. 209-214, 1965. Discussion of axle-load daily variation and seasonal variation.

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Chu, M. L.; Doyle, G. R.; "Experimental Verification of Linear Random Vibration Theory as Applied to a Four-Wheel Vehicle Traversing a Random Terrain," JASA Abstract, V55, Supplement, p. 52, 1974. Analytical model of vibration of vehicle and experimental results from simulator.

Kurze, U. J.; "Statistics of Road Traffic Noise," J. of Snd. & Vib., 1971, V18, N2, pp. 171-195. Analytical determination of the statistical parameters of traffic noise. The probability distribution, the mean and the variance of the sound pressure level are calculated.

Johnson, D. R.; Saunders, E. G.; "The Evaluation of Noise from Freely Flowing Road Traffic," J. of Snd. & Vib., 1968, V7, N2, pp. 287-309. Results of sound level surveys taken at a variety of locations and of road traffic types. Examines the effect of velocity, the immediate surroundings and of gradients. Some equations are derived.

Yeow, K. W.; "A Stochastic Model of the Noise Field Emitted from Traffic in Steady Flow," J. of Snd. & Vib., 1974, V32, N2, pp. 227-239. Assumes steady-flow is equal to statistically stationary traffic flow. A theoretical model is developed.

Peters, S.; "The Prediction of Railway Noise Profiles," J. of Snd. & Vib., 1974, V32, N1, pp. 87-99. A method for predicting the rise and decay of the noise emitted from a passing train is presented.

Reiter, W. F., Jr.; Hart, F. D.; "Experimental Investigation of the Vibrational Characteristics of Truck Tires," JASA Abstract, V51, N1, Prt. 1, 1972, p. 88. Results of an experiment to obtain the data necessary to describe the vibrational behavior of truck tires, effects of pressure, tread, and load on frequency and mode shapes and the relationship between sidewall and tread vibration.

Reiter, W. H.; Harper, L. J.; Eberhardt, A. C.; "In Service Tire Vibration Investigation," JASA Abstract, V53, N1, 1973, p. 306. Experimental data obtained for tire sound and vibration for understanding tire noise generating mechanisms and influence of load, tread type, tread wear and speed.

Copley, L. G.; "Consulting Experience with the New Federal Highway Noise Standards," JASA Abstract, V53, N1, 1973, p. 305. The paper addresses procedural aspects of the standards.

A.1.1.2 HIGHWAY DESIGN, CONSTRUCTION, AND MAINTENANCE STANDARDS

Bernhard, R. K.; "Highway Investigation by Means of Induced Vibration," Penn State Col. Bull., Engr. Exp. Stn., Bull. No. 49, V33, 1939. The results of tests to determine properties of the highway and the subsoil. Straight forward equations given for propagation speed in lower strata and depth of strata. Curve of amplitude vs. distance provided.

"Penn State's Continuing Pavement Test is Yielding Valuable Research Results," Highway Research News, N53, Winter '73, pp. 20-21. Tests performed to check various bridge surfaces and highway materials. Soil pressure and stress on soil and pavement is monitored. Skid tests being performed.

Virchis, V. J.; Robson, J. D.; "Response of an Accelerating Vehicle to Random Road Undulation," J. of Snd. & Vib., Oct. '71, V18, N3, pp 423-427. Analytical procedure developed for vehicle itself. Experimental results applied to analytical procedure.

Robson, J. D.; "Deductions from the Spectra of Vehicle Response Due to Road Profile Excitation," J. of Snd. & Vib., V7, N2, pp 156-158, 1968. Response of the vehicle. Relationship between varying velocities and vehicle response.

Foley, J. T.; Gens, M. B.; Magnuson, C. F; "Current Predictive Models of the Dynamic Environment of Transportation," J. Environmental Sciences, V16, N1, JA/FE '73, pp. 18-28. The dynamic environment experienced by cargo during transport.

Priede, T.; "Noise and Vibration Problems in Commercial Vehicles," J. of Snd. & Vib., V5, pp. 129-154, 1967. Experimental results of noise and vibration in the vehicle cab, at the curbside and in the cargo department. Emphasis is on noise and vibration in the cab.

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Priede, T.; "Origins of Automotive Vehicle Noise," J. of Snd. & Vib., 1971, V15, N1, pp. 61-73. Characteristics of the noise produced by the various major elements of a vehicle are discussed. It is shown that the noise emitted by the vehicle elements is determined primarily by the operational speed.

Aspinall, D. T.; "Control of Road Noise by Vehicle Design," J. of Snd. & Vib., V13, N4, 1970, pp. 435-444. A discussion of noise control for vehicles to reduce both the internal and the external noise levels.

Waters, P. E.; "Control of Road Noise by Vehicle Operation," J. of Snd. & Vib., 1970, V13, N4, pp. 445-453. Presentation of some preliminary investigations into the noise emitted by road vehicles under various operating conditions. It is found that noise at constant speed increases at a mean rate of 12 dBA per doubling of distance.

Kurze, U. J.; "Noise from Complex Road Traffic," J. of Snd. & Vib., 1971, V19, N2, pp. 167-177. Statistical parameters are derived. Noise from freely flowling traffic calculated considering traffic mixes, numerous roads, barriers, and other influences that can be approximated by the superposition of contributions from statistically independent elements.

Nayak, P. R.; "Surface-Roughness Effects in Rolling Contact," J. of Applied Mechanics, V39, N2, June '72, pp. 456-460. An analytical procedure is developed to explain surface-roughness. The solution is most applicable when the normal load is low or the surface roughness is high.

Dodds, C. J.; Robson, J. D.; "The Description of Road Surface Roughness," J. of Snd. & Vib., 1973, V31, N2, pp. 175-183. The development of an analytical technique to describe road surface undulations which can be used to describe vehicle response. Solution is the result of an assumption that road surfaces may be considered as realizations of homogeneous and isotropic two-dimensional Gaussian random processes.

Williams, T. E. H.; "Highway Engineering and the Influence of Geometric Design Characteristics on Noise," J. of Snd. & Vib., V15, N1, 8 Mar. '71, pp. 17-22. General discussion of noise from traffic and those things which can be done to the highway or along the right of ways to lower noise levels. Table of day/night noise levels for a variety of roads.

Bor, W.; "Urban Transport and Environment," J. of Snd. & Vib., 1971, V15, N1, pp. 41-51. General discussion of the conflicts between a good urban environment and the needs of transport is developed. Using established common ground on five issues, a plan of attack is proffered.

Brown, S. F.; Bush, D. I.; "Dynamic Response of Model Pavement Structure," Transpor. Engr. J., ASCE, V98, TE4, Proc. Pap. 9363, Nov. '72, pp. 1005-1022. In-situ measurements of stress, strain and deflection in a lab model pavement subjected to dynamic loading is reported. Aim of the test was to check the validity of linear elastic theoretical solutions to the three layer system.

Robbins, E. G.; Warnes, C. E.; "Traffic Data for Concrete Pavement Design," Transpor. Engr. J., ASCE, V99, TE1, Proc. Pap. 9555, Feb. '73, pp. 17-29. Reported in this paper is the development of generalized traffic data representative of road and street type. It is for use with computer program PCCHWY.

Phang, W. A.; "Vehicle Weight Regulation and the Effects of Increased Loading on Pavements," Dept. of Highways, Ontario, DHO Report No. RR 151, Nov. '69, pp. 16. A comparison of the effects of increased loading on flexible and rigid pavements is made with some recommendations for the future.

Casgoly, P. F.; Campbell, T. I.; Agarwal, A. C.; "Bridge Vibration Study," Ministry of Transportation and Communications, MTC Report No. 181, Sep. '72, pp. 30. A computer program is the basis of this comprehensive study. Free vibration theory is examined with comparisons of theoretical and experimental results made also.

Jung, F. W.: "Simplified Design Live Load Patterns for Use in Controlling Vehicle Weights on Bridges," Dept. of Highways, Ontario, D40 Report No. RR 149, Sep. '69. This report is a study in general mathematical terms, of the effect of axle group loads on the forces and moments of continuous and simply supported bridge structures. The approach is deterministic rather than statistical, having validity for a limited range of bridge spans.

Veletsos, A. S.; Tseng Huang: "Analysis of Dynamic Response of Highway Bridges," J. Engr. Mech. Div., ASCE, V96, EM5, Oct. '70, pp. 593-620. Analytical technique is developed to describe both the vehicle and the bridge, their motions and the constraints to be used to compute the dynamic response of highway bridges under the action of moving vehicles.

Page, J.; "Impact Tests on Pipes Buried under Roads," RRL Report No. 35, Road Research Laboratory, Ministry of Transport, Crowthorne, 1966. The results of tests to determine impact factor and dynamic strains are reported for four types of vehicles on both smooth and rough surfaces.

Brown, P. P.; "Airfield Pavement Evaluation Procedures," J. Aerospace Transportation Div., ASCE, V91, AT1, Proc. Pap. 4299, April '65, pp. 15-31. A summary of current procedures describing methods of appraising surface conditions; in place and lab test determination of load capacity and procedures for converting a multi-wheel system to a single wheel load system is provided.

Yang, N. C.; "Interaction of Aircraft and Ground Structure," J. Struct. Div., ASCE, V96, Prt. 1, ST6, Proc. Pap. 7360, June '70, pp. 1119-1142. Derives an analytical procedure to account for aircraft response, structure response, and pavement response to the excitations created when the rolling aircraft traverses rough surfaces.

Burt, J. O.; Leblanc, E. J.; "Res. Report No. 75, Res. Proj. No. 71-3C(B), Louisiana HPR 1(11), Louisiana Dept. of Hwys., March '74. Results of a study of the vibration of luminaires located at bridges and overpasses and the various dampers tested to suppress these vibrations are reported.

A.1.2 ENVIRONMENTAL VIBRATIONS

Ferahian, R. H.; Graefe, P. W. U.; "Comparison of Earthquake, Blast, and Pulse Excitations, "Engr. Journ., V55, N3, March '72, pp. 12-19. The results of a comparison of the response spectra for the acceleration of three types of forcing function are discussed. Graphs of acceleration amplitude vs. frequency or time are presented for the three functions.

Gray, G. G.; Johnson, K. L.; "The Dynamic Response of Elastic Bodies in Rolling Contact to Random Roughness of their Surfaces," J. of Snd. & Vib., 1972, V22, N3, pp. 323-342. The theory and techniques of random vibration are applied to this study to assess the fluctuations in the contact force for a wheel or a rail. Both theoretical and experimental results are obtained.

A.1.2.1 SONIC BOOMS

Goforth, T. T.; McDonald, J. A.; "A Physical Interpretation of Seismic Waves Induced by Sonic Booms," J. Geophys. Res., V75, Prt. 5, No. 26, pp. 5087-5092, 1970. Assuming that aircraft flying level and unaccelerated isequivalent to a static load, a computer program is run to compare experimental and theoretical results. Figures showing the comparisons is given.

Cook, J. C.; Goforth, T.; Cook, R. K.; "Seismic and Underwater Responses to Sonic Boom," J. Acous. Soc. America, V51, No. 2, Prt. 3, 1972, pp. 729-741. This report is a summary of work done in relation to seismic and underwater responses to sonic boom. Both experimental and theoretical results are included. It compares the maximum particle velocity resulting from a sonic boom as being equal to the velocity resulting from a car passing at 30 mph, 30 feet away on a paved road. Velocity profiles are included.

Cook, J. C.; Goforth, T. T.; "Ground Motion from Sonic Booms," J. of Aircraft, AIAA, Mar. '70, V7, N2, pp. 126, 129. A general discussion of criterion for building damage (2/M/SEC), equipment used to measure seismic responses, and results of some experimental results.

Espinosa, A. F.; Siera, J. P.; Mickey, M. V.; "Seismic Waves Generated by Sonic Booms: A Geoacoustical Problem," J. Acous. Soc. Amer., V44, N4, 1968, pp. 1074-1082. The observations derived from experimental measurements of seismic waves generated by sonic-booms. Figures showing relative amplitude vs. period are presented.

Dalins, I.; McCarty, V.M.; Kaschak, G.; Donn, W. L.; "Observation of Early Arriving Seismic Signal from Appolo 16 Launch," JASA Abstract, V52, N5, Prt. 1, 1972, p. 1312. Discussion of rocket-generated seismic disturbances and signal characteristics, analysis techniques and instrumentation is given.

Dalins, I.; McCarty, V. M.; "Strong Seismic Wave Generation Mechanisms During Large Rocket Launches and Static Tests," JASA Abstract, V51, N1, prt. 1, 1972, p. 146. Provided is a discussion of three types of waves generated during launch and static firings, their propagation and characteristics along with instrumentation to measure.

Weber, G.; "Sonic Boom Exposure Effects II.1: Structures and Terrain," J. of Snd. & Vib., Feb. '72, V20, N4, pp. 505-509. This report is a general discussion and evaluation of effects of sonic booms on topographical features and ground motion effects on structures and a discussion of structural parameters.

Warren, C. H. E., "Recent Sonic-Bang Studies in the United Kingdom," J. Acous. Soc. Amer., V51, N2, Prt. 3, 1972, pp. 783-789. This paper cites the results of recent sonic-boom studies including experimental results of the influence of sonic-booms on greenhouses, cathedrals, and other historic and non-historic structures.

Pauagadhi, L. J.; Yajnik, M. D.; "Vibration of Circular Elastic Plates Due to Sonic Boom," Acous. Soc. Amer., V52, N1, Prt. 2, 1972, pp. 260-269. An analytical formula is developed to describe the response of large circular plates to axisymetric transient vibrations. The resulting solution is then applied to three structural materials with the aid of a computer. Plots of dynamic deflection are given.

Crocker, M. J.; Hudson, R. R.; "Structure Response to Sonic Booms," J. of Snd. & Vib., 1969, V9, N3, pp. 454-468. Using an idealized mathematical expression to represent an N-Wave and considering structural members as a mass-spring-damper system, the various sonic-boom parameters are varied to determine their relative influence on structural response.

Clarkson, B. L.; Mayes, W. H.; "Sonic-Boom Induced Building Structure Responses Including Damage, "J. Acous. Soc. Amer., V51, N2, Prt. 3, 1972, pp. 742-757. This article is a comprehensive study on structure response to airborne waves, including sections on the response and damage to historic buildings. The study includes some analysis and experimental results.

Hubbard, H. H.; Mayes, W. H.; "Sonic Boom Effects on People and Structures," NASA SP-147, National Aeronautical & Space Adm., Langley Research Center, 1967. A general discussion of the effects of sonic-boom overpressures on the responses of persons inside and outside a dwelling and the response of the structure to airborne waves. Figures showing the effect of rise time and duration on the plots of relative amplitude vs. frequency are also shown.

Rylander, R.; Sorenson, S.; Andrae, B. O.; Chatelier, G.; Espmark, Y.; Larsson, T.; Thackray, R. I.; "Sonic Boom Exposure Effects - A Field Study on Humans & Animals, "J. of Snd. & Vib., 1974, V33, N4, pp. 471-486. Explained in this report is the result of a field experiment to study the reactions of humans after exposure to sonic-booms with special reference to startle reactions. Animal responses were monitored also.

May, D. N.; "The Loudness of Sonic Booms Heard Outdoors as Simple Functions of Overpressure and Rise Time," J. of Snd. & Vib., 1971, V18, N1, pp. 31-43. In this study a comparison is made between some derived semi-empirical formulas with accepted theoretical loudness calculations in the prediction of the loudness of sonic booms heard outside. An experimental as well as analytical assessment was made.

A.1.2.2. RAILWAY OPERATION VIBRATIONS

Nayak, P. R.; "Contact Vibrations," J. of Snd. & Vib., V22, N3, 1972, pp. 297-322. This paper develops some of the theoretical groundwork necessary for detailed physical explanations of experimentally observed phenomona in vibratory point contact. Three cases are analyzed: undamped free vibrations, forced damped vibrations with sinusoidal input, and vibrations with broadband random input.

Nayak, P. R.; "Contact Vibrations of a Wheel on a Rail," J. of Snd. & Vib., 1973, V28, N2, pp. 277-293. An analytical model is developed to explain high-frequency contact vibrations.

Bender, E. K.; "Noise and Vibration of Resiliently Supported Track Slabs," J. Acoust. Soc. Amer., V55, N2, Beb. '74, pp. 259-268. This paper examines an analytical model of the dynamic response, vibration isolation, and sound radiation of resiliently supported track slab.

Nishiki, T., Shiraishi, S.; "Overloads on Japan's 130-MPH Railroad Structures," J. Struct. Div., ASCE, V96, Prt. I, ST6, Proc. Pap. 7325, June '70, pp. 1017-1023. Provided in this paper is a general discussion of the live loads carried by trains and the corresponding frequency.

Drew, F. P.; "Loading Histories," Proceedings of AREA Seminar; Munse, W. H.; Stallmeyer, J. E.; Drew, F. P. (Ed); Amer. Railway Engr. Assoc., 59 East Van Buren St., Chicago, Ill., 1968. This article provides results of tests conducted at train bridges to determine their loading histories during train passage. Results are plotted in block diagram form.

Brown, L. M; "Effect of Construction Equipment Vibration on Nearby Buildings," Ontario Dept. of Transportation & Communications, pp. 117-131. Summarization of the various criteria that have been used to evaluate damage. States that tests have shown that velocity is the best indicator of damage. Graphs of velocity vs. distance for five types of construction equipment performing a variety of tasks is included.

Brown, L. M.; "Measurements of Vibrations Caused by Construction Equipment and Blasting," Ontario Dept. of Highways, DHO Report No. RR172, April '71, pp. 61. A comprehensive review of both experimental and general analytical methods related to vibrations from blasting and construction. Discusses safe limits, human sensitivity, effects on dwellings, attenuation with distance and other subjects. Several figures representing results of vibration tests are provided.

Tiedmann, D. A.; "Ground Motions from Vibratory Roller Compaction of Cohesive Soil," Bureau of Reclamation, U.S. Dept. Interior, REC-OCE-70-28, June '70, pp. 22. Experimental results in graphic form are reported and discussed for applicability with any corresponding detrimental effects the vibrations may have.

A.1.2.5 BLASTING VIBRATIONS

Nicholss, H. R.; Johnson, C. F.; Duvall, W. I.; "Blasting Vibrations and their Effects on Structures," Bureau of Mines, U. S. Dept. of the Interior, Bulletin 656, 1971, 101 pp. A comprehensive overview of blasting vibrations, both air and ground vibrations, including instrumentation, safe vibration levels for dwelling, generation and propagation of vibration waves and methods for estimation of safe vibration levels. Contains both analytical methods and experimental results. Velocity profiles as a function of frequency are provided.

Davies, J. V.; "Ground Vibrations from Tunnel Blasting," Tunnels and Tunnelling, V2, N3, pp. 141-144, May 1970. This article includes a general discussion of the properties of a ground wave, formulas for predicting amplitude, effect of vibration on buildings and a criterion for damage is established.

Duvall, W. I.; Fogelson, D. E.; "Review of Criteria for Estimating Damage to Residences from Blasting Vibrations," Report of Investigation 5968, TN23, V7, U.S. Dept. Interior, Bureau of Mines, 1962, 19 pp. This is a review of investigations into what quantity is the best indicator of building damage followed by recommendations for damage criteria. Criteria is presented in the form of graphs of displacement and velocity as a function of frequency.

Bollinger, G. A.; Blast Vibration Analysis, Southern Illinois University Press, 1971, 132 pp. This is a complete book covering the physics of wave motion, the generation of seismic waves from blasting, the measurement of blast vibrations, analysis of blast seismograms, and damage criteria and effects of vibrations.

Thau, S. A.; "Motion of a Finite Rigid Strip in an Elastic Half Space Subjected to Blast Wave Loading," Intrnl. J. of Solids and Structures, V7, N2, pp. 193-211, 1971. An analytical model is arrived at to describe the motion of an obstacle imbedded in a half-space and subjected to blast waves. The scattering of elastic waves by diffraction and radiation is considered.

Isenberg, J.: Lee, L: Agbabian, M. S.: "Response of Structures to Combined Blast Effects," Transport Engr. J., ASEE, V99, TE4, Proc. Pap. 10166, Nov. '73, pp. 887-908. Provides methods of computing dynamic structural response due to combined air blast and ground shock loading. Comparisons are made between experimental measurements and analytical computations.

Harper, M. J.; Hawkins, S. J.; Hicks, J. A.; "Explosively Generated Air Pressure Waves for Structural Forcing," J. of Snd. & Vib., 1970, V11, N2, pp. 217-224. Explained is the use of aerial blasts to determine the response of structures.

A.1.3 VIBRATION STANDARDS AND CRITERIA

Armstrong, M. D.; Jung, F. W.; Phang, W. A.; "A Proposed Method of Regulating Vehicle Weights in Ontario," Dept. of Highways, Ontario, DHO Report No. 166, Sept. 1970, 25 pp. Discusses vehicle weight regulation proposed which use axle weights and a "bridge formula." The purpose of the regulation is to permit the greatest payload without causing abnormal damage.

Crocker, M. J.; "Vibration Control and Biodynamics," JASA Abstract, V51, N1, Prt. 1, 1972, p. 116. This is a summary of different papers offered on this subject.

Fishman, B.; "ISO/TC 108 - Mechanical Vibration and Shock," J. of Environmental Sciences, V16, N1, Ja/Fe '73, pp. 29-32. General overview of the group that determines vibration criteria and limits.

A.2.1.2 SOIL TESTING TECHNIQUES

Van Zelst, T. W.; "Geophysical Instruments in Highway Planning," Presented at the Regional Conference, International Road Federation, Lima, Peru, May 17-27, 1965. Describes equipment available for testing soils and determining parameters of subsoils and how to use this equipment.

Davis, L. L.; West, L. R.; "Observed Effects of Topography on Ground Motion," Bull. Seismo Soc. Amer., V63, N1, pp. 283-298, Fef. '73. Topography plays a significant role and is an important consideration in determining the seismic motion that a particular site receives according to this study. This conclusion is the result of the interpretations of data obtained from field experiments.

Lysmer, J.; Seed, H. B.; Schwabel, P. B.; "Influence of Base-Rock Characteristics on Ground Response," Bull. Seismo Soc. Amer., V61, N5, pp. 1213-1231, Oct. '71. Response characteristics of nine typical soil deposits over different types of base-rock are studied to evaluate the influence of base-rock on surface accelerations. Conclusions are based on experimental data. Graphs comparing accelerations as functions of wave periods for ground surface motions and base-rock motions are included.

Dezfulian, H.; Seed, H. B.; "Response of Non-Uniform Soil Deposits to Travelling Seismic Waves," J. Soil Mech & Founda Div., ASCE, V97, Prt. 1, SM1, Proc. Pap. 7808, Jan. '71, pp. 27-46. Provides effects of local soil condition on the amplitude and frequency characteristics of ground surface motion. Experimental results are reported.

Nelson, I.; Baron, M. L.; "Application of Variable Moduli Models to Soil Behavior," Intrnl. J. of Solids & Structures, 1971, V7, N4, pp. 399-417. A mathematical model to describe the action of soils under both static and/or dynamic loads is developed in terms of the incremental stress-strain relations. The model is examined for uniaxial strain and triaxial compression because of the availability of these soil tests.

D'Appolonia, E.; "Dynamic Loadings," J. Soil Mech. & Founda. Div., ASCE, V96, Prt. 1, SM1, Proc. Pap. 7010, Jan. '70, pp. 49-72. Methods used to place and improve soil in situ for the support of structures are appraised Also presented are criteria used to assure tolerable deformation of structures during dynamic loadings.

A.2.2.1 WAVE PROPAGATION: ANALYTICAL DESCRIPTION

Richart, F. E., Jr.; Hall, J. R., Jr.; Woods, R. D.; Vibrations of Soils and Foundations, Prentice-Hall, Inc., 1970, Englewood Cliffs, New Jersey. This is a complete book covering such topics as vibrations of elementary systems, wave propagation in an elastic, homogeneous, isotropic medium, elastic waves in layered media, behavior of dynamically loaded soils, theories for vibration of foundations on elastic media, instrumentations, and design procedures.

Ben-Amoz, M.; "The Effective Wave Velocities of Heterogeneous Materials," Intrnl. J. Engr., SCI, V7, N10, pp. 990-1019, 1969. The effective wave velocities and impedances of a two-phase elastic solids are determined by an approximate analytical method.

Beaudet, P. R.; "Elastic Wave Propagation in Heterogeneous Media," Bull. Seismo Soc. Amer., V60, N3, pp. 769-784, 1970. An analytical wave equation is derived then solved for the ensemble average of particle displacements produced by an explosion. The results are compared with field observations from underground nuclear tests.

Chwalczyk, F.; Rafa, J.; Wlodarczyk, E.; "Propagation of Two Dimensional Non-Stationary Stress Waves in a Semi-infinite Viscoelastic Body, Produced by a Normal Load Moving Over the Surface with Subseismic Velocity," Proceedings of Vib. Prob., V13, N3, pp. 241-257, 1972. An analytical closed-form solution to the propagation problem of non-stationary two-dimensional stress waves of the Boltzmann type is obtained. The waves are produced by a pressure uniformly distributed along a line and moving with subseismic velocity.

Dunkin, J. W.; Corbin, D. G.; "Deformation of a Layered Elastic Half-Space by a Uniformly Moving Line Loads, "Bull. Seismo Soc. Amer., V60, N1, pp. 167-191, Feb. '70. As described in this article, for uniformly moving line loads along the surface, the deformation of the half-space depends on the manner in which the load couples into the surface-wave modes.

Keer, L. M.; "Moving and Simultaneously Fluctuating Loads on an Elastic Half-Plane," J. Acous. Soc. Amer., V47, N5, Prt. 2, pp. 1559-1565, 1970. An analytical procedure is arrived at and solved for the combined problem of moving and simultaneously fluctuating line loads. It is found that symetrical load distributions will result in a displacement response beneath the load that is asymmetric.

Norwood, F. R.; "Interior Motion of an Elastic Half-Space Due to a Normal Finite Moving Line Load on its Surface," Intrnl. J. of Solids & Structures, V6, N12, pp. 1483-1498, 1970. In this reference an analytical exact expression is derived for the transient response of a half-space to normal finite load moving on its surface. The solution is found to be a superposition of cylindrical, hemispherical, conical and plane waves.

Daniel, I. M.; Marino, R. L.; "Wave Propagation in a Layered Model Due to Point Source Loading in a High-Impedance Medium," Geophysics, V36, N3, June '71, pp. 517-532. Dynamic photoelastic techniques are used to study the Incident, reflected and refracted waves in a layered model. The experimental results are studies of propagation and attenuation characteristics of waves in both layers.

Wolf, B.; "Propagation of Love Waves in Layers with Irregular Boundaries," Pure Applied Geophysics, V78, N1, pp. 48-57, 1970. An analytical study is made of the scattered field which results when a Love wave is incident on layer having an irregular surface.

Clements, D. L.; Rogers, C.; "On Wave Propagation in Inhogeneous Elastic Media," Intrnl. J. of Solids & Structures, V10, N6, Prt. 1, pp. 661-679, 1974. An analytical technique in the form of matrix transformations is used to describe wave propagation in an inhomogeneous elastic radar slab.

Borcherot, R. D.; "Rayleigh-Type Surface Wave on a Linear Viscoelastic Half-Space," J. Acous. Soc. Amer., V54, N6, pp. 1651-1653, 1973. An analytical solution for this problem is arrived at. The velocity, absorption coefficient, and displacement field are described theoretically.

Sidhu, R. S.; "Transmission of Rayleigh Waves the Surface of a Heterogeneous Medium," Pure Applied Geophysics, V80, N3, pp. 48-70, 1970. A purely analytical dissertation is presented for the derivation of the frequency equation for Rayleigh wave propagation in the medium.

Bose, S. K.; Chatterjee, A. K.; "On the Vibration of a Wall Due to Plane P, S, and Rayleigh Waves," Intrnl. J. Engr. Sci, 1972, V10, pp. 729-742. The analytical solution to the problem described in the title is solved.

Tsai, N. C.; Housner, G. W.; "Calculation of Surface Motions of a Layered Half-Space," Bull. Seismo Soc. Amer., V60, N5, pp. 1625-1651, Oct. '70. An exact and an approximate computational model is presented for digital transient analysis of a set of linearly viscoelastic layers on an elastic half-space with vertically-travelling waves. Calculated responses are compared with recorded motions.

Christensen, R. M.; "Wave Propagation in Elastic Media with a Periodic Array of Discrete Inclusions," J. Acous. Soc. Amer., V55, N4, pp. 700-707, 1974. This study concerns the propagation of time harmonic waves in a continuous medium in which is imbedded a three-dimensional periodic array of discrete inclusions. This work tries to account for multiple-reflection effects between inclusions. A steady-state solution is obtained.

Wolf, A.; "The Equation of Motion of a Geophone on the Surface of an Elastic Earth," Geophysics, V9, pp. 29-35, 1944. A mathematical model is developed to account for the varying elastic module values of the earth and the damping effect involved in the response of the geophone.

Wood, D. H.; "Parameterless Examples of Wave Propagation," J. Acous. Soc. Amer.; V54, N6, 1973, pp. 1727-1736. Examples of wave propagation are analytically derived in parameterless form.

Schoenberg, M.; "Plane Wave Propagation in Stratified Anisotropic Media," J. Acous. Soc. Amer., V55, N5, pp. 922-925, 1974. Given is an analytical solution to the problem of sinusoidal plane waves propagating in stratified medium, each layer of which is elastic homogeneous and fully anisotropic.

Thurston, G. B.; Shi-Yu Wu; "Dilational-Wave Transmission through a Viscoelastic Layer at Normal Incidence, J. Acous. Soc. Amer., V34, N5, 1962, pp. 653-644. The theory of transmission of a plane wave through an infinite plane layer is considered where the media involved are assumed to be lineraly viscoelastic, their properties specified by four elastic constants.

Smith, P. G.; Greenkorn, R. A.; "Theory of Acoustical Wave Propagation in Porous Media," J. Acous. Soc. Amer., V52, N1, Prt. 2, 1972, pp. 247-253. A theory is developed to describe the propagation of sound waves in a rigid isotropic and homogeneous porous medium filled with a compressible fluid, including both the effect of viscous dissipation and the effect of thermal conduction. The analytical results are compared with independent experimental results.

Wright, J. P.; Baron, M. L.; "Exponentially Decaying Pressure Pulse Moving with Constant Velocity on the Surface of a Layered Elastic Material (Super Seismic Layer, Subseismic Half-Space)," J. Applied Mech., V37, N1, pp. 141-152, 1970. An analytical procedure is developed to describe the response of a layered elastic half-space to a progressing exponentially decaying normal surface pressure. A computer program for evaluating stresses and velocities at points in the medium is developed and results are presented for a typical configuration of interest.

Henzi, A. N.; Dally, J. W.; "A Photoelastic Study of Stress Wave Propagation in a Quarter-Plane," Geophysics, V36, N2, Apr. '71, pp. 296-310. The results of an experimental investigation conducted on a quarter-plane loaded with an explosive charge at one point on the boundary. Results are obtained for both the P and R-wave interaction with the corner.

Mason, I. M.; "Anisotropy, Diffraction Scaling, Surface Wave Lenses, and Focusing," J. Acous. Soc. Amer., V53, N4, 1973, pp. 1123-1128. Analytical formulation to explain wave phenomena associated with lenses, specifically anisotropic diffraction. Experimental results that illustrate the principal conclusions are presented.

Tsai, S. C.; Ong, E. C.; Tan, B. P.; Wong, P. H.; "Applications of the Z-Transform Method to the Solution of the Wave Equation," J. of Snd. & Vib., 1971, V19, N1, pp. 17-20. The one-dimensional wave equation is solved using the z-transform method.

Thapliyal, V.; "The Combined Effects of Transverse Isotropy and Inhomogeneity on Love Waves," Bull. Seismo. Soc. Amer., V63, N1, pp. 49-57, Feb. '73. An analytical formulation defining the characteristic frequency equation for Love waves propagating in a finite layer overlying an anisotropic and inhomogeneous half-space is derived.

"The Propagation of Waves in Elastic Solid Media," Love, A.E.H.; <u>A Treatise on the Mathematical Theory of Elasticity</u>, Fourth Edition, Dover Publications, N.Y., 1944, pp. 293-309. An analytical formulation and discussion of wave propagation in elastic solid media. Begins with a description of the motion at distances away from the source in all directions.

Warburton, G. B.; "Forced Vibrations of a Body on an Elastic Stratum," J. of Applied Mech., March 1957, pp. 55-58. An analytical procedure to describe the response of a solid body on an elastic stratum under the influence of forced vibrations. The theoretical results obtained are compared with experimental results.

Timoshenko, S.; Goodier, J. N.; Theory of Elasticity, pp. 362-372 only, 2nd Edition, McGraw-Hill Book Co., Inc. 1951. Analytical discussion of the force on the boundary of a semi-infinite body and the load distributed over a part of the boundary of a semi-infinite solid.

Hayes, M. A.; Rivlin, R. S.; "Propagation of Sinusoidal Small-Amplitude Waves in a Deformed Viscoelastic Solids," J. Acous. Soc. Amer., V51, N5, Prt. 2, 1972, pp 1652-1663. Analytically, the mean energy flux vector for a plane sinusoidal wave of small-amplitude is calculated. Also considered are the internal reflection of an SH wave at the plane surface of a half-space, and the reflection-refraction problem at the plane interface between two half spaces.

Baum, D. W.; Smith, W. R.; "Propagation of Elastic Waves in a Cylindrical Bar Subject to a Moving Load on its Lateral Surface," J. Acous. Soc. Amer., V52, N5, Prt. 2, 1972, pp. 1421-1429. Presented are the results of a theoretical and experimental study of the elastic strain produced in a cylindrical bar by a moving step function load on the lateral surface.

Kirchner, R. P.; Herman, H.; "Fundamental Frequency Approximation Method," J. Acous. Soc. Amer., V55, N6, 1974, pp. 1225-1231. Using the vibration of a sandwich plate as an example, the effectiveness of some methods of obtaining one-term approximations for the lowest eigenvalue of coupled systems is evaluated.

Kouskoula, V.; Barnard, R.; "Time-Spectral Energy Density - Some of its Properties," JASA Letter to the Editor, V55, N2, Feb. '74, pp. 357-358. The physical meaningfulness of the time-spectral energy concept and a relation to the corresponding output of a linear system are established.

Galbraith, E. W.; Barton, M. V.; "Ground Loading from Footsteps," JASA Letter to the Editor, V48, N5, Prt. 2, 1970, pp. 1288-1292. Reported are the results of a series of laboratory experiments to measure the load-time histories of the input to the ground from footsteps.

Robson, J.D.; "Note on the Harmonic Analogy for Random Vibration Response," J. of Snd. & Vib., V31, N3, pp. 388-389, 1973. Letter to the Editor. Analytical discussion of an earlier work.

White, J. E.; Seismic Waves: Radiation, Transmission and Attenuation, McGraw-Hill Book Co., 1965, 302 pp. This is a complete book covering the topics of plane waves, loss mechanisms and attenuation, waves along cylindrical boreholes, sources of elastic waves, seismic model experiments and small-scale field experiments.

Singh, S. K.; Kuo, J. T.; "Response of an Elastic Half-Space to Uniformly Moving Circular Surface Loads," J. of Applied Mech., V37, N1, Mar. '70, pp. 109-115. The solution to the problem of a uniformly moving circular surface load for uniform and hemispherical load distribution is given. The displacement components for the two cases are obtained in integral form.

Gakenheimer, D. C.; "Response of an Elastic Half-Space to Expanding Surface Loads," J. of Applied Mech., V38, N1, Mar. '71, pp. 99-110. The problem of axisymmetric, normally applied, surface loads is solved analytically for loads that suddenly emanate from a point on the surface, expanding radially at a constant rate.

A.2.2.2 WAVE PROPAGATION: EXPERIMENTAL DESCRIPTION AND TECHNIQUES

"Traffic Induced Vibrations in the Yuma Territorial Prison Area," Proj. No. N800-210, AFE 10A31, Contract No. 72-3, Feb. 5 & 6, 1972. Structural Behavior Engineering International, Phoenix, Ariz. A description of testing equipment, location, and procedure are provided along with the results of the experiment.

A.2.2.3 WAVE PROPAGATION: EXPERIMENTAL DATA

Jennings, P. C.; "Distant Motions from a Building Vibration Test," Bull. Seismo. Soc. Amer., V60, N6, pp. 2037-2043, Dec. '70. This report discusses the merits of inducing ground motion through excitation of a multistory building. Horizontal and vertical accelerations were measured during such a test.

Douglas, B. M.; Weir, P.; "Multistory Building Response Determined from Ground Velocity Records," Bull. Seismo. Soc. Amer., V62, N1, pp. 357-367. The response of a multistory building to the excitations induced from an underground nuclear blast are reported. The velocity of the ground and of the roof are presented.

Shepherd, R.; Charleson, A. W.; "Experimental Determination of the Dynamic Properties of a Bridge Structure," Bull. Seismo. Soc. Amer., V61, N6, pp. 1529-1548, Dec. '71. Presented here are the results of a series of steady-state vibration tests undertaken on a multispan continuous deck bridge. The method of testing is outlined and the measured natural frequencies given.

Szendrel, M. E.; Freeme, C. R.; "Road Responses to Vibration Tests," J. Soil Mech. and Founda. Div., ASCE, V96, Prt. 2, SM6, Proc. Pap. 7709, Nov. '70, pp. 2099-2124. Assuming that pavement behaves in a linear elastic manner, pavement was subjected to various wheel loads. Wave propagation and attenuation measurements were made as well as impedance measurements. Curves of deflection as a function distance and time are shown for a moving load.

Kurzeme, M.; "In-Situ Investigation Using SH-Waves," J. Soil Mech. & Founda. Div., ASCE, V97, SM2, Prt. 1, Proc. Pap. 7918, Feb. '71, pp. 341-356. Horizontally polarized shear waves are generated at the surface of layered road pavements and soil structures to observe the resulting velocity dispersion with frequency. The experimental dispersion plots are compared with theoretical dispersion plots.

Moore, P. J.; "Calculated and Observed Vibration Amplitudes," J. Soil Mech. & Founda. Div., ASCE, V97, Prt. 1, SM1, Proc. Pap. 7789, Jan. '71, pp. 141-158. A comparison is made between observed and calculated maximum displacement amplitudes for small footing on three types of soils. The analytical description of displacement amplitudes at or near resonance for vibrations induced by reciprocating machinery is examined.

A.2.3 WAVE ATTENUATION

Becker, F. L.; Richardson, R. L.; "Influence of Material Properties on Rayleigh Critical-Angle Reflectivity," J. Acous. Soc. Amer., V51, N5, Prt. 2, pp. 1609-1617. This work is an investigation of critical-angle phenomena and the relationship between material properties and the condition for which zero reflectivity occurs. Graphs are presented for several materials for which the critical angle for a particular sample may be determined.

A.2.3.1 WAVE ATTENUATION: ANALYTICAL DESCRIPTION

Alsop, L. E.; Goodman, A. S.; Ash, E.; "Surface Wave Dispersion in a Mass-Loaded Half-Space," J. Acous. Soc. Amer., V50, N1, prt. 2, pp. 176-180, 1971. The effect of pure mass loading is solved analytically along with a determination of under what conditions the neglect of the elastic restraining forces is justifiable.

Schwab, F.; Knopoff, L.; "Surface-Wave Dispersion Computations," Bull. Seismo. Soc. Amer., V60, N2, pp. 321-344, 1970. Fundamental-mode Love- and Rayleigh-wave dispersion computations for multilayered, perfectly elastic media are studied using a computer program analysis.

White, J. E.; Walsh, D. J.; "Proposed Attenuation-Dispersion Pair for Seismic Waves," Geophysics, V37, N3, pp. 456-461, June '72. By modeling one-dimensional seismic waves as propagation along a simple lumped-element transmission line, expressions for attenuation and velocity as functions of frequency are found which not only satisfy the experimental data available, but exhibit no objectionable behavior outside the range of available data. It is the author's opinion that velocity is substantially independent of frequency.

Hang-Sheng Tuan; Li, R. C. M.; "Rayleigh-Wave Reflection from Groove and Step Discontinuities," J. Acous. Soc. Amer., V55, N6, June '74, pp. 1212-1217. An analytical technique, using a boundary-perturbation method is employed to determine the reflection of a Rayleigh wave from either a shallow groove or a low step in the surface of an isotropic elastic half-space.

Kudo, K.; Shima, E.; "Attenuation of Shear Waves in Soil," Bull. Earthquake Res. Institute, V48, 1970, pp. 145-158. Data obtained from field experiment to measure velocity at various distances from the source. Results are plotted in the form of attenuation coefficient as a function of frequency.

Kudo, K.; Allam, A. M.; Anda, I.; Shima, E.; "Attenuation of Love Waves in Soil Layers," Bull. Earthquake Res. Institute, V48, Prt. 2, 1970, pp. 159-170. Experimental results are presented for the investigation into the attenuation coefficient of Love Waves in the frequency range from 4.5 to 11 cps.

Negi, J. G.; Upadhyay, S. K.; "Love Wave Dispersion: Errors Due to Assumption of Isotropy," Pure Applied Geophysics, V80, N3, pp. 102-107, 1970. Analytically, the frequency for Love Waves, propagating in a transversely isotropic homogeneous layer which is embedded between two isotropic homogeneous half spaces, is obtained. Errors in the assumption of isotropy are calculated by numerically analyzing the frequency equation.

Slavin, L. M.; Wolf, B.; "Scattering of Love Waves in a Surface Layer with an Irregular Boundary for the Case of a Rigid Underlying Half-Space," Bull. Seismo. Soc. Amer., V60, N3, pp. 859-877, 1970. An analytical method is presented which is useful for obtaining the scattered field due to a Love Wave incident upon a local boundary irregularity in the elastic layer along which the wave is propagating.

Snowden, J. C.; Kerlin, R. L.; "Vibration Attenuation with Beams -- Theory and Reciprocal Experiment," J. Acous. Soc. Amer., V51, N1, Prt. 2, 1972, pp. 249-264. This report indicates the reciprocal measurements substantiated theoretical prediction that significant regions of attenuation exist in the transmissibility curves of cantilever beams driven by dual forces of the same magnitude and force.

A.2.3.3. WAVE ATTENUATION: EXPERIMENTAL DATA

Hardin, B. O.; Drnevich, V. P.; "Shear Modulus and Damping in Soils: Measurement and Parameter Effects," J. Soil Mech. and Founda. Div., ASCE, V98, SM6, Prt. 1, Proc. Pap. 6977, June '72, pp. 603-624. The results of field tests are used to show how the controlling parameters affect the stress-strain relations of soils subjected to simple shear.

Hardin, B. O.; Drnevich, V. P.; "Shear Modulus and Damping in Soils: Design Equations and Curves," J. Soil Mech. and Founda. Div., ASCE, V98, SM7, Prt. 2, Proc. Pap. 9006, July '72, pp. 667-692. Presented here are equations and graphs for the determination of shear modulus and damping of soils, for use in design problems involving repeated loading or vibration of soils. These equations and graphs are based on numerous test results.

Blume, J. A.; "The Motion and Damping of Buildings Relative to Seismic Response Spectra," Bull. Seismo. Soc. Amer., V60, N1, pp. 231-259, Feb. '70. Shown and reported in this report are data and equations that are useful in determining the relationships of seismic spectral response and the response of buildings modeled as lumped mass systems. Graphs of acceleration as a function of time are presented.

A.2.4.2 COUNTERMEASURE TECHNIQUES: TRENCH DESIGN

Woods, R. D.; Richart, F. E., Jr.; "Screening of Elastic Surface Waves by Trenches," Proceedings of International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, Albuquerque, New Mexico, 1967. Field-model tests performed to determine the effectiveness of open trenches for screening Rayleigh waves developed by model footings undergoing vertical oscillations. A comprehensive overview of the experimental program and of the results is given.

A.2.4.3 COUNTERMEASURE TECHNIQUES: BARRIER DESIGN

Aboudi, J.; "The Motion Excited by an Impulsive Source in an Elastic Half-Space with a Surface Obstacle," Bull. Seismo. Soc. Amer., V61, N3, pp. 747-763, June 1971. Analytically defined in this report is an elastic half-space having a surface obstacle of slightly different elastic constants whose deviation and shape of boundaries are small.

Aboundi, J.; " Elastic Waves in Half-Space with Thin Barrier," J. Engr. Mech. Div., ASCE, V99, EM1, pp. 69-83, Proc. Pap. 9536, Feb. '73. The effects of a vertical thin barrier of an arbitrary depth imbedded within an elastic half-space is solved for analytically.

Harmelink, M. D.; Hajek, J. J.; "Noise Barrier Evaluation and Alternatives for Highway Noise Control," Ministry of Transportation and Communications, M.T.C. Report No. RR180, Sep. '70. Results of field sound measurements are reported, evaluating various highway noise shielding techniques then comparing the results with those calculated by a theoretical noise estimation method.

A.3.2 STRUCTURAL RESPONSE

Gurpinar, A.; Yao, J. T. P.; "Design of Columns for Seismic Loads," J. Structural Div., ASCE, V99, Prt. 3, ST9, Proc. Pap. 9978, Sep. '73, pp. 1875-1889. Obtained in this work is the analytical solution for the coupled problem of instability. The probability of failure is computed for a number of columns subjected to design loads as well as certain earthquake excitations.

Suidan, M. T.; Eubanks, R. A.; "Cumulative Fatigue Damage in Seismic Structures," J. Structural Div., ASCE, V99, Prt. 2, ST5, May 1973, pp. 923-943. Analytical and experimental results are presented analyzing the response of structures to a series of earthquake. One conclusion reached by the authors is that cumulative fatigue damage is of a degree warranting consideration in the design.

Veletsos, A. S.; Vann, W. P.; "Response of Ground-Excited Elastoplastic Systems," J. Structural Div., ASCE, V97, Prt. 1, ST4, Proc. Pap. 8075, Apr. 1971, pp. 1257-1281. Reported in this work are the results of an investigation to identify the parameters which have a dominant influence on the response of multi-degree-of-freedom elastoplastic system of the shear-beam type when subjected to deterministically specified ground motions.

Isada, N. M.; "Damage to Structures Due to Floor Shocks," J. Struct. Div., V97, Prt. 1, St2, Proc. Pap. 7897, Feb. 1971, pp. 561-572. The factors that affect the impending damage and failure of structural bent-type structures due to pulse-type floor acceleration shocks are determined analytically. A computer program is used to simulate sources and responses.

Brown, C. B.; "Seismic Energy Transmission to Deep-Founded Structures," Bull. Seismo. Soc. Amer., V61, N3, pp. 781-787, June 1971. A general analytical procedure is developed to estimate building response when the structural foundation is deep-founded causing Rayleigh-wave attenuation and associated changes in seismic input.

Anderson, G. L., "On the Forced Vibrations of Elastic Bodies in Contact," J. of Snd. & Vib., 1971, V16, N4, pp. 533-549. Formulated in this work is the analytical method of solving the problem of forced vibrations of two elastic bodies having a surface of contact, using the framework of the classical, linear theory of elasticity.

Solie, L. P.; Auld, B. A.; "Elastic Waves in Free Anisotropic Plates," J. Acous. Soc. Amer., V54, N1, pp. 50-65, 1973. The mathematical formalism for obtaining dispersion relations for acoustic waves in plates of arbitrary anisotropy is outlined in this report and the dispersion curves for propagation of a specific material are presented.

Wang, W. M.; "Filter Design for Vibration Isolation between Multi-Resonant Structures," J. of Snd. & Vib., 1971, V16, N3, pp. 309-314. A mechanical filter design for vibration isolation between multi-resonant structures is presented.

Davies, H. G.; "Exact Solutions for the Response of Some Coupled Multimodal Systems," J. Acous. Soc. Amer., V51, N1, Prt. 2, pp. 387-392, 1972. This paper presents exact solutions for the response to excitation of some idealized models of coupled multimodal systems. The systems treated are assumed continuous, exhibiting only small transverse vibratory responses to applied transverse loadings.

A.3.2.1 SOIL-FOUNDATION COUPLING

Remington, P. J.; "The Response of a Plate Bonded to a Randomly Vibrating Viscoelastic Half-Space," J. Acous. Soc. Amer., V51, N3, Prt. 2, pp. 974-984, 1972. Calculated in this report is the response of an infinite Bernoulli-Euler plate placed on the surface of a randomly vibrating viscoelastic half-space, allowing for the presence of shear stresses between the plate and the half-space.

Luco, J. E.; Westmann, R. A.; "Dynamic Response of a Rigid Footing Bonded to an Elastic Half-Space." J. of Applied Mechanics, V39, N2, June, 1972. Dynamic force-displacements relationships for harmonic transverse motion of a rigid strip footing perfectly bonded to the surface of an elastic half-space are obtained. The footing is subjected to vertical, shear, and moment forces with harmonic time-dependence.

Scavuzzo, R. J.; Raftopoulos, D. D.; Bailey, J. L.; "Lateral Structure Interaction with Seismic Waves." J. of Applied Mechanics, V38, N1, pp. 125-134, 1971. By making use of normal mode theory and the solution of a half-space problem in which displacements are caused by a shear stress varying arbitrarily with time over an area symmetric about the origin, lateral interaction between a structure and the half-space can be expressed by an integral equation of the Volterra type according to this author.

Scavuzzo, R. J.; Raftopoulos, D. D.; Bailey, J. L.; "Lateral Structure-Foundation Interaction of Structures with Base Masses." Bull. Seismo. Soc. Amer., V62, N2, pp. 453-470, Apr. '72. The analytical formulation of the interaction of structures with heavy base masses to lateral inertia forces reduces to an integral equation of the Volterra type as stated in this report.

Jennings, P. C.; Bielak, J.; "Dynamics of Building-Soil Interaction Bull. Seismo. Soc. Amer., V63, N1, pp. 9-48, Feb. '73. Modeling the soil as a linear elastic half-space and a building structure as an n-degree-of-freedom oscillator, analytical methods are developed to enable the response computation for multistory structures to earthquake excitations. Comparisons are made between measured responses and theoretical curves for acceleration, velocity and displacement.

Lee, I. K.; Harrison, H. B.; "Structure and Foundation Interaction Theory," J. Struct. Div., ASCE, V96, Prt. 2, ST2, Proc. Pap. 7059, Feb. '70, pp. 177-197. In this report analytical methods derived for the analysis of combined footings and two-dimensional raft foundations which take into account the effect of the rigidity of the superstructure on the distribution of forces and moments transmitted to the foundation.

Sarrazin, M. A.; Roesset, J. M.; Whitman, R. V.; "Dynamic Soil-Structure Interaction," J. Struct. Div., ASCE, V98, Prt. 2, ST7, July '72, pp. 1525-1544. Using dimensionless parameters a study is made of soil-structure interaction. Instead of finding results for one specific, real or simulated, earthquake, average values are obtained by considering the root mean square response to a white noise input, and by averaging the maximum responses to a set of several artificial records with the same statistical characteristics.

Parmelee, R. A.; Wronkiewicz, J. H.; "Seismic Design of Soil-Structure Interaction Systems," J. Struct. Div., ASCE, V97, Prt. 3, ST 10, Proc. Pap. 8437, Oct. 1971, pp. 2503-2517. The importance of characterizing the dynamic properties of the foundation medium and the structure medium for describing soil-structure phenomena is analytically shown in this report.

"Plates on Elastic Foundation," Timoshenko, S.; Woinowsky-Krieger, S.; Theory of Plates and Shells, pp. 259-281, 343-347, McGraw-Hill Book Company, Inc., 1959. The sections of the book represented here cover calculation of deflection by the strain energy method, analytical study laterally loaded plates on elastic foundations.

Luco, J. E.; Contesse, L.; "Dynamic Structure-Soil-Structure Interaction," Bull. Seismo. Soc. Amer., V63, N4, pp. 1289-1303, Aug. '73. The steady-state response and dynamic interaction of two parallel infinite shear walls placed on rigid foundations is studied and analytically solved for the case of vertically incident S4 waves then compared to corresponding values resulting from consideration of only one structure.

Morgan, J. R.; Moore, P. J.; "Application of Soil Dynamics to Foundation Design," pp. 465-527, from Soil Mechanics, Selected Topics; Lee, J. K. (Ed.), American Elsevier Publishing Company, New York, 1968. These sections of the book cover the problem of vibrating foundations, theory of vibrations, design of vibrating foundations, strength of various types of soils, effect of rate of deformation on rigidity and a comparison of static and dynamic moduli for soils.

Rainer, J. H.; "Structure-Ground Interaction in Earthquakes," J. Engr. Mech. Div., ASCE, V97, EM5, Proc. Pap. 8422, Oct. 1971, pp. 1431-1450. A method of analysis is presented that utilizes the transformation of a single-story interaction structure into an equivalent single-degree-of-freedom model to determine the response of interaction systems under earthquake type disturbances.

Fagel, L. W.; Shih-Chi Liu, "Earthquake Interaction for Multistory Buildings," J. Engr. Mech. Div., ASCE, V98, EM4, Proc. Pap. 9149, Aug. 1972, pp. 929-945. Allowing for the frequency-dependent nature of the interaction forces between soil and foundation, a technique employing the Fast Fourier Transform system is used to analyze the response of multistory buildings. Interaction forces are defined from solutions for a general class of boundary-value problems involving a rigid plate bonded to an elastic half space and sybjected to harmonic motion.

Tezcan, S. S.; "Earthquake Design Formula Considering Local Soil Conditions," J. Struct. Div., ASCE, V97, ST9, Proc. Pap. 8399, Sep. 1971, pp. 2383-2405. An empirical formula that incorporates several important parameters relating to both soil and structure response to vibration is proposed for the purpose of evaluating the seismic forces induced for use as an earthquake design formula.

Seed, H. B.; Idriss, I. M.; "Influence of Soil Conditions on Building Damage Potential During Earthquakes," J. Structural Div., ASCE, V97, Prt. 1, ST2, Proc. Pap. 7909, Feb. 1971, pp. 639-663. An analysis of records from past earthquakes is done to show how soil conditions affect the response of buildings and how records of soil-structures parameters can be used to anticipate the response of buildings.

Remington, P. J.; Crandall, S. H.; "Response of a Covering Plate to Noise in a Viscoelastic Half-Space," J. Acous. Soc. Amer., V48, N5, Prt. 2, 1970, pp. 1170-1178. The frequency spectrum of the response of an infinite plate when it is placed on a randomly vibrating viscoelastic half-space is calculated for the case of no shear stress between the plate and the half-space. Experimental measurements are made then compared with theoretical results.

Warburton, G. B.; Richardson, J. D.; Webster, J. J.; "Forced Vibrations of Two Masses on an Elastic Half-Space," J. Applied Mechanics, V38, N1, Mar. 1971, pp. 148-156. A theory is presented for the vibrations of two masses attached to the surface of an elastic half-space, when subjected to periodic forces and moments. Results for two geometrically identical cylindrical masses excited by a vertical harmonic force applied to one of the masses, illustrate the effect of the presence of a second mass upon the response of the excited mass and the conditions for which the response of the second mass is significant.

Awojobi, A. O.; "Determination of the Dynamic Shear Modulus and the Depth of the Dominant Layer of a Vibrating Elastic Medium," Intrnl. J. Solids Structures, V6, N3, pp. 315-322, 1970. The author of this article implies that the assumption that a foundation can be regarded as an isotropic half-space is in error. He corrects this error by first establishing in a novel manner the depth of this dominant layer and then determining its shear modulus.

A.3.2.2 VIBRATION CHARACTERISTICS OF BUILDING STRUCTURES

Davenport, A. G.; "The Treatment of Wind Loadings on Tall Buildings," Tall Buildings, Proceedings of a Symposium on Tall Buildings, Southampton, April 1966, pp. 3-45. This paper surveys the significant features of the interaction of a tall building with the wind and indicates the approaches available for making quantitative estimates of key design parameters. The wind turbulence is described statistically.

Davenport, H. G.; "The Buffeting of Large Superficial Structure by Atmosphere Turbulence;" Annals of the New York Academy of Sciences, V116, Article 2, pp. 135-159, June 26, 1964. The statistical concepts of the stationary random series is briefly outlined in this work as a framework to correlate the fluctuating components of wind velocity to the response of a structure.

Ward, H. S.; Crawford, R.; "Wind-Induced Vibrations and Building Modes," Reprint from Bull. Seismo. Soc. Amer., V56, N4, August 1966, pp. 793-813. This paper outlines the methods that have been used to determine the frequencies and modes of vibration of multistory buildings from their wind-induced vibration. Three buildings were experimentally investigated to determine modes and frequency of vibrations. A simple theoretical model was also used to calculate frequency of vibration.

Crawford, R.; Ward, H. S.; "Determination of the Natural Periods of Buildings," Reprinted from Bull. Seismo Soc. Amer., V54, N6, December 1964, pp. 1743-1756. Experimental measurements of a nineteen story building are made with the results being analized on an analog computer to determine the first three modes of vibration. Theoretical computations of the modes were also made using simplifing assumptions.

Reddy, N. N.; Lowery, R. L.; "Transient Response of Double Acoustical Resonators to Excitation by a Single Sine Wave," J. of Snd. & Vib., 1970, V12, N2, pp. 165-175. Using a lumped parameter representation of a double acoustical resonator, an analytical solution is arrived at to describe the response of the resonator to a transient sine wave.

Nigul, U.; "Plane Stress Waves in Membranes Caused by an Arbitrary Pressure Wave," J. Acous. Soc. Amer., V51, N1, Prt. 2, pp. 241-248, 1972. Using the example of the plane motion of a membrane, an analytical method is developed for finding the approximate solution of the second-order wave equation whose right-hand side describes a pressure wave moving with decreasing velocity.

Nayfeh, A. H.; "Mook, D. T.; Seshadri, S.; "Non-linear Analysis of the Forced Response of Structural Elements," J. Acous. Soc. Amer., V55, N2, pp. 281-291, 1974. A general analytical procedure is presented for the nonlinear analysis of the forced response of structural elements to harmonic excitations.

Gellert, M.; Gluck, J.; Grebel, M.; Posner, C. H.; "Analysis of Elastic Stiffened Plates with Undefinable," Build. Sci., V8, pp. 79-85, 1973. A method of analysis of orthogonally stiffened elastic plates with undefinable middle plane is presented in this study. Differential equations of equilibrium and expressions for boundary conditions in terms of displacement are established.

Yang, T. Y.; Sun, C. T.; "Axial-Flexural Vibration of Frameworks Using Finite-Element Approach," J. Acous. Soc. Amer., V53, N1, pp. 137-146, 1973. An analytical method for predicting the frequency of axial-flexural coupling vibration of frameworks, using a finite element method, is presented. The article shows that axial vibration is important especially for tall buildings because vertical motion of a seismic wave is very substantial.

Ray, D. P.; Sinha, P. K.; "On the Flexural Behavior of Orthotropic Sandwich Plates;" Build. Sci., V8, pp. 127-136, 1973. In this work a general analytical procedure of determining the flexural behavior of plates is presented, considering the orthotropic sandwich plates as having orthotropic faces and core, unequal face thicknesses and dissimilarities in face materials.

Trifunac, M. D.; "Ambient Vibration Test of a Thirty-Nine Story Steel Frame Building;" Earthquake Engr. Res. Lab., EERL-70-02, July 1970, Calif. Inst. Tech., 40 pp. The results of a field experiment determine higher order frequency shapes of the translational and torsional vibrations are presented in this study. A description of instrumentation for both data collection and reduction is included.

Anon.; "Vibrations in Buildings;" Building Research Station Digest, No. 78, June 1955, 7 pp. This is a general discussion of vibrations in buildings and human sensitivity to vibration. It discusses experimental work that has been performed and presents graphs of frequency as a function of amplitude with lines of the degree of human annoyance and possibility of building damage overlayed on the graph.

Anon.; "Vibrations in Buildings - 1;" Building Research Station Digest, No. 117, 1970, 8 pp. This work contains an explanation of some of the terms used in vibration studies and their relationships, human sensitivity to vibration - the Reiher-Meister and Dieckman scales, and vibration and damage to buildings.

Anon.; "Vibration in Buildings - 2;" Building Research Station Digest, No. 118, June 1970, 8 pp. This general report discusses some of the ways in which nuisance from vibrations can be avoided or reduced to tolerable leve-by treatment at the source, by reducing the transmission of vibration and by providing protection against vibration from an external source.

Rao, V. V. S.; Singh, S.; "Behavior of Block Foundations Subjected to Ground Vibrations;" Indian Concrete Journal, June 1971, V45, N6, pp. 258-61, 269-270. This paper presents the results of a model study of block foundations subjected to vertical ground motions. A description of the experimental set-up and procedure is given.

Jacquot, R. G.; Soedel, W.; "Vibrations of Elastic Surface Systems Carrying Dynamic Elements," J. Acous. Soc. Amer., V47, N5, Prt. 2, 1970, pp. 1354-1358. The problem of determining the natural frequencies and associated mode shapes of a continuous elastic system combined with other dynamic elements is solved in general, analytically.

Peyrot, A. H.; "Probabilistic Response of Nonlinear Buildings During Earthquakes;" J. Struct. Div., ASCE, V98, Prt. 3, ST11, Nov. 1972, pp. 2363-2380. A digitally produced earthquake is used to excite an analog mode of a building structure for consideration of the dynamics of nonlinear hysteretic multistory buildings when subjected to a random excitation of the earthquake type.

Shinozuka, M.; Yang, J-N.; "Peak Structural Response to Non-Stationary Random Excitations," J. of Snd. & Vib., V16, N4, pp. 505-517, 1971. Dealing with dynamic responses that can be treated as a non-stationary narrow-band random process, this paper establishes the distribution function of peak values with useful frequency interpretation. The validity of the distribution function is checked by a numerical simulation of the peak values.

Hurst, H. T.; Lezotte, H. R.; "A Comparison of Vibrational Characteristics of Wooden Floor Construction," Build. Sci., V5, pp. 105-109, 1970. Concentrated loads applied to wooden floor systems of different designs were released suddenly in these field experiments with resulting vertical vibrations being recorded. The results show the effects of joist size.

Ng, S. F.; Kulkarni, G. G.; "On The Transverse Free Vibration of Beam-Slab Type Highway Bridges," J. of Snd. & Vib., 1972, V21, N3, pp. 249-261. A general outline of an analytical procedure and computed values of natural frequencies of vibration of bridge slabs for a wide range of parameters are given in this report, using a set of empirical relationships between the plate parameters.

Tso, W. K.; "Stresses in Coupled Shear Walls Induced by Foundation Deformation," Building Science, V7, pp. 197-203, 1972. Based on the continuum method, closed form solutions are obtained to give the internal forces and moments induced in shear walls due to foundations settlement and rotation. A numerical example is presented.

Tso, W. K.; Biswas, J. K.; "An Approximate Seismic Analysis of Coupled Shear Walls," Build. Sci., V7, pp. 249-256, 1972. By first obtaining the dynamic characteristics of a structure approximately, taking the vibrating cantilever modes as the approximate mode shapes of the structure, the frequencies of the structure can be obtained by means of Rayleigh's principle according to this article. The resulting frequencies obtained are then compared with those calculated from dynamic analysis.

Bhattacharya, M. C.; Mulholland, K. A.; Crocker, M. J.; "Propagation of Sound Energy by Vibration Transmission Via Structural Junctions," J. of Snd. & Vib., 1971, V18, N2, pp. 221-234. The analysis presented in this paper shows that when flexural and longitudinal waves are propagated across a wall junction, a wave interaction with mode transformation and with gain or loss in the amplitudes takes place.

Genin, J.; Radwan, H.; "Non-Linear Vibrations of a Beam on a Visco-elastic Foundation," J. of Snd. & Vib., 1971, V18, N2, pp. 197-201. In this paper, the equation of motion for transverse vibrations of a slender beam on a continuous viscoelastic foundation is derived and analyzed.

Cusens, A. R.; Zeidan, M. A.; Pama, R. P.; "Elastic Rigidities of Ribbed Plates," Build. Sci., V7, pp. 23-32, 1972. An analytical method is developed for plates reinforced with an orthogonal system of eccentric ribs of rectangular section, which enables the accurate determination of elastic rigidities in flexure and torsion. Results from this analytical method are compared with experimental values obtained from tests.

Popescu, N. D.; "Dynamical Stability of the Flexure Stressed Straight Beams Under the Action of a Mobile Convoy of Loads," Build. Sci., V7, pp. 131-141, 1972. An examination of the problem described by the title is undertaken in this study resulting in analytical procedure for determining critical speeds, the strains and the dynamic coefficient. It is shown that mobile loads acting on a beam can force the beam to enter resonance.

A.3.2.4 BUILDING DESIGN STANDARDS

Hardy, A. C.; Lewis, P. T.; "Sound Insulation Standards for Buildings Adjacent to Urban Motorways," J. of Snd. & Vib., 1971, V15, N1, pp. 53-59, Reported in this study are the results of an investigation of the amplitude and frequency distribution of traffic noise, attenuation of traffic noise by buildings, and the effect of the transmitted noise on the internal environment. It is suggested that this data be used for design of new buildings adjacent to urban motorways.

A.3.2.5 BUILDING DAMAGE CRITERIA

Anon.; "Cracking in Buildings," Building Research Station Digest, No. 75, (2nd Series), 1966, 8 pp. This report is a general discussion of several factors that can cause or affect cracks in buildings. Which factors affect which materials is delineated for correct diagnosis and repair.

Scholl, R. E.; Farhoomand, I.; "Statistical Correlation of Observed Ground Motion with Low-Rise Building Damage," Bull. Seismo. Soc. Amer., V63, N5, pp. 1515-1537, Oct. '73. This report provides the results of a statistical study conducted correlating ground motion with structure damage data from underground nuclear explosion gas simulation experiment. An identification of the ground motion characterization that best represents the damage potential of ground motion is arrived at then motion damage relationships for low-rise buildings is developed.

A.4.1 ENVIRONMENTAL LAWS REGULATING VIBRATION

"Legislation", pp. 179-205, from Doerdon, C.; Noise Abatement, New York Philosophical Library, 1971. This chapter of the book deals with legislation in effect in Great Britain dealing with noise control, using adjudicated cases it defines the law and explains where the law may be applicable.

"Summary of Environmental Impact Analysis, Stone Mountain Tollway," prepared by J. E. Greiner Company, Inc., Consulting Engineers. This EIS contains a section on acoustic noise and one on seismic noise. An estimate is made of maximum particle velocity anticipated and the number of homes to be affected by various noise levels.

A.4.2 ADJUDICATED CASES RESULTING FROM VIBRATION

Brazener, R. A.; "Annotation: Traffic Noise and Vibration from Highway as Element of Damages in Eminent Domain," American Law Reporter, 51ALR3d, 1973, Lawyer Cooperative Publishing Co., pp. 860-897. This annotation collects cases which confront the issue of whether traffic noise or vibration emanating from a public highway constitutes a separate element of damages in eminent domain proceedings.

APPENDIX II

ASSESSMENT OF COMPLAINT DATA AND ADJUDICATED CASES

The assessment of complaint data and adjudicated cases resulting from traffic-induced vibration forms a basis for defining the nature of the problem. It is necessary to define the problem in terms of technical criteria relating quantities describing the vibration source, the vibration propagation, and the effects of vibration on buildings and people. To complement the description of technical criteria, it was necessary to determine the frequency of occurrence and the problem of traffic-induced vibration as encountered by highway engineers in the field. Additionally, an assessment of the occurrence of litigation and trends in the court's judgement relative to traffic-induced vibration cases was conducted to indicate any significant factors.

Using this approach, it is felt that the necessary technical criteria can be cast in a form useful to highway engineers that will reflect both the field situations expected and provide an assessment of potential legal implications associated with traffic-induced vibration.

Compilation of Complaint Data

During the initial phase of this task, the use of a formal questionnaire to determine the nature and occurrence of complaints and litigation relative to the traffic-induced vibration problem was deemed impractical due to the wide range of situations encountered. Therefore, during the reporting period telephone contacts were made, as recommended by FHWA, with their Regional Offices concerning reports of complaints related to traffic-induced vibration. FHWA Regional personnel then directed the inquiries to appropriate state and municipal agencies.

As described above, contacts were made initially by telephone with a formal letter following as appropriate. These letters requested specific information in those cases where the agencies had experienced highway-related vibration problems. A typical letter request and response is included at the end of the appendix as a representative sample.

The compilation of initial complaint data (without detail) that resulted from the initial efforts of this task are presented in Table AII-1 and provided the procedural basis for locating complaint data relative to the traffic-induced vibration problem. For reference, Figure AII-1 is presented illustrating the FHWA Regions and the location of state and municipal agencies contacted. The absence of a contact in either a FHWA Region or a state does not imply that no problems were encountered in that region or state. Indeed, all municipal agencies contacted had experienced some form of traffic-induced vibration; however, only 45% of the municipalities

TABLE AII-1. SUMMARY OF COMPLAINTS WITHOUT DETAIL
(Continued)

State/FHWA Region	Nature of Concern and/or Complaint	Status of Inquiry
Alabama/4	Red Mountain Expressway, Birmingham Expressway routed near an apartment	Concern alleviated by P.R. work by the contractor
Arizona/9	Traffic Induced Vibrations in the Yuma Territorial Prison Area (1972)	Engineering Report provided by Arizona DOT
Georgia/4	Environmental Assessment/Stone Mountain Tollway Traffic Induced Vibrations at Observatories	Engineering Report provided by Georgia DOT
	Structural Degradations to Rhodes Mansion Historical Building in Atlanta	Engineering Report and Data Available
	Individual complaint of traffic vibrations from Interstate 20, Atlanta	
Kentucky/4	Watterson Expressway, Louisville Public concerns expressed during planning	Concerns apparently alleviated
Louisiana/6	Bridge/Luminaire Vibration Suppression Study - Luminaire life study resulting from bridge traffic induced vibrations	Engineering Report provided by Louisiana DOT
	Seismic Vibration due to Pile Driving - Engineering Report in preparation by Louisiana DOT	
	Traffic Induced Vibration of Historic Buildings in the Vieux Carre (New Orleans, La.)	
	Traffic Induced Vibration in the Garden District from traffic on Mississippi River Bridge (B.R. 90)	
Maryland/3	Concern that highway noise and vibration would disrupt activity of a school or hospital, Baltimore	

TABLE AII-1. SUMMARY OF COMPLAINTS WITHOUT DETAIL
(Concluded)

State/FHWA Region	Nature of Concern and/or Complaint	Status of Inquiry
North Carolina/4	Highway or railway vibration of house (EPA complaint), Hendersonville	
Ohio/5	Building vibration resulting from proposed highway alignment, Dayton	
Pennsylvania/3	Concern about vehicle-induced vibration in residences at six locations in Philadelphia. Southeastern Pennsylvania Transit Authority buses alleged to cause problems.	SEPTA works closely with municipal agencies responsible for street repair and makes strong effort to control bus speed in troubled areas
Tennessee/4	St. Judes Hospital, Memphis - concern about highway vibrations with proposed highway alignment	Concern apparently alleviated
Washington/10	Concern about proposed highway alignment near a hospital, Spokane	

have responded to the inquiries as of the reporting date. The above approach resulted in a compilation of 68 instances of highway-related vibration problems of which 51 cases were well documented by either site reports or extensive engineering studies presenting soil data, vibration measurements, and in one case, vehicle "bump" tests.

Mr. John Orrison, Chief Structural Design Engineer, Department of Public Works, City of Atlanta, became aware of this activity and our interest in traffic-induced vibration and offered information on 25 documented complaints from residents of Metropolitan Atlanta.

Assessment of Complaint Data

A total of 68 complaints have been reviewed. Fifty-one of the complaints are well documented and 17 are not. There have been numerous unofficial complaints described by individuals during conversations related to vibrations related to highway use. For example, professors in the Aerospace Engineering Department at Georgia Institute of Technology, Atlanta, Georgia, say that students frequently experience disruption of laboratory tests involving delicate and precision instruments because of bus and heavy truck traffic on streets adjacent to the Aerospace Engineering Building.

A summary of the 51 well documented complaints is given in Table AII-2. A careful study of the table shows that a majority of the complaints were made by individuals concerning their home located within 400 feet of the street imperfection. Most of the complaints involved annoyance; however, there were three cases where both annoyance and building damage were indicated. Heavy trucks and buses were alleged to cause most of the problems. Traffic speed was considered as an important factor in only eight percent of the cases. However, there were strong opinions in the cases where speed was mentioned that a lowering of the speed solved or minimized the problem. Rough road surfaces involving manhole covers, storm drains, etc., were considered to cause 53 percent of the complaints, whereas, 25 percent of the structural vibration problems were believed to be a result of chuck holes, open ditches, etc. Building vibrations and soil tests were made by some of the investigators. Road repairs and modifications were accomplished for 63 percent of the cases and, apparently, in most instances satisfied the complaintant. Two cases involving litigation were mentioned.

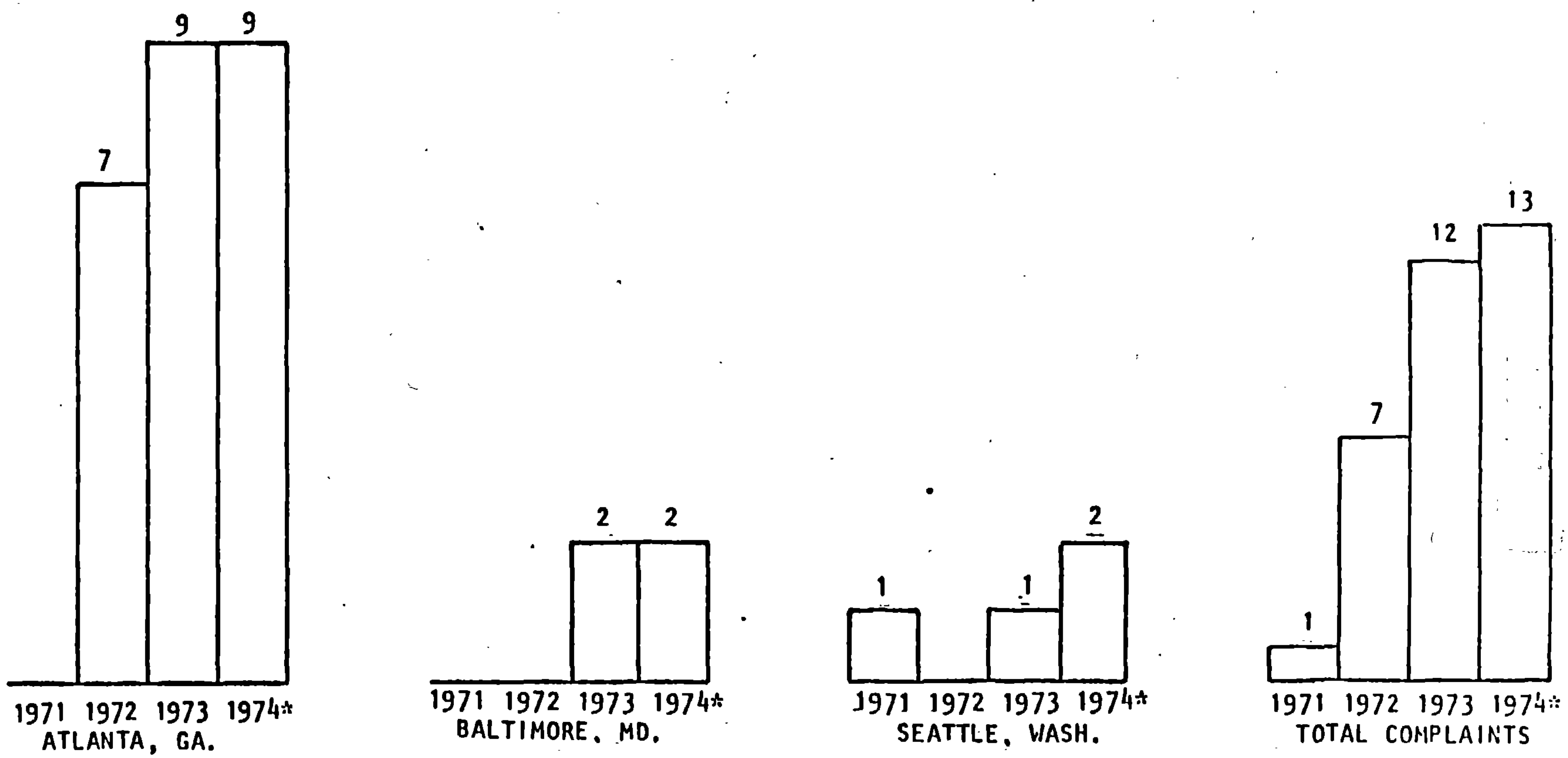
A summary of the remaining 16 complaints is presented in Table AII-1.

After studying the complaint information from the 51 well documented cases, it is concluded that, since 1971, the number of complaints related to highway induced vibration is on the increase. Figure AII-1 is a graphical presentation of 34 complaints recorded in Atlanta, Georgia; Baltimore, Maryland; and Seattle, Washington for the years of 1971 through October 1972. Even though the sample size is small, an increasing trend is indicated.

TABLE AII-3

SUMMARY OF COMPLAINT DATA FOR TRAFFIC-INDUCED VIBRATIONS

COMPLAINT CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
INDIVIDUAL ACTION	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	O	O	O	O		O	O	O	O		O		O	O	O	O	O	O		O	O
GROUP ACTION																O																			O					O									O		
PRIVATE RESIDENCE	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	O		O	O	O		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	
RENTAL PROPERTY																																																O			O
COMMERCIAL PROPERTY																							O				⊕				O																				
WITHIN 400' OF SOURCE	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O	O	O	O	O	O	O	O	O		O	O		O	O	O	O	O	O	O				O			O
BEYOND 400' OF SOURCE																																																			
ANNOYANCE	O	O	O	O				O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O								O	O	O	O	O	O	O	O	O	O	O	O				O			
BUILDING DAMAGE					O											O										O	O	O	O	O	O				O	O									O	O	O		O	O	O
NOISE MENTIONED																												O	O		O	O			O																
HEAVY VEHICLES ONLY				O		O	O	O					O							O				O	O			⦶	O	O	O	O	O	O		O	O		O	O	O	O	O	O	O						O	O
ALL TRAFFIC														O											O									O			O						O		O	O	O	O	O		
TRAFFIC SPEED A FACTOR																											O																			O	O		O		
DAMAGED ROAD SURFACE	O				O								O	O								O								O		O			O	O					O			O			O				O
ROUGH ROAD SURFACE		O		O		O		O	O	O		O	O	O	O	O	O	O			O	O	O	O				O			O		O	O			O			O					O	O		O	O		
UNKNOWN ROAD SURFACE			⦶				O				O								O	O					O	O	O		O									O	O			O	O							O	
SITE LAYOUT AVAILABLE					O	O												O		O	O					O	O	O	O	O	O	O	O			O															
SOIL DATA AVAILABLE																O														O		O							O	O				O				O	O		
VIBRATION DATA AVAILABLE																										O	O	O	O	O	O	O	O									O			O						
ROAD MAINTENANCE PERFORMED	O	O		O	O	O						O	O	O	O	O	O	O	O	O	O	O	O	O				O		O		O		O	O	O	O	O		O	O			O	O		O				O
OTHER CORRECTIVE MEASURES																																	O													O					
NO ACTION TAKEN																										O	O	O	O		O								O			O						O	O		
LITIGATION INVOLVED																									O																	O									
CLAIMS PAID																																																			
WINTER								O						O	O	O	O																												O	O	O	O		O	O
SPRING									O									O	O	O	O															O		O		O									O		
SUMMER	O	O								O	O											O				O					O	O	O				O				O	O	O	O							
FALL			O	O	O	O	O					O	O										O	O	O					O					O				O												
REMARKS	⊕ CHURCH ⦶ PAVEMENT REMOVAL EQUIPMENT																																																		



* COMPLAINTS RECORDED THROUGH OCTOBER 31, 1974

FIGURE AII-2 TRAFFIC-INDUCED VIBRATION COMPLAINTS BY YEAR FOR THREE METROPOLITAN AREAS

Assessment of Adjudicated Cases

To extend the assessment of the complaint data presented above, a brief compilation and evaluation of the adjudicated cases resulting from highway-related vibration problems was accomplished using the data presented in Appendix III. The objective of this effort was to establish any trend that might be apparent related to decisions for or against a plaintiff in a traffic-induced vibration litigation.

Table AII-3 presents a summary of 19 adjudicated cases listed in Table AII-4 resulting from highway-related vibration problems during the period of 1963 through 1972. From the data presented in Table AII-3, it is seen that a majority of the adjudicated cases involved single individuals and private property (residences). Eleven of the 19 cases involved annoyance. Home or building structural damage was claimed for the remaining eight cases. Noise was mentioned as an annoying factor in 15 cases. Heavy highway vehicles and road construction machinery were alleged to cause the problem in 14 of the 19 cases. Fifty-three percent of the adjudicated cases were decided in favor of the plaintiff.

Based upon the 19 adjudicated cases resulting from highway-related vibration problems during the 1963-1972 period, it is concluded that, since 1968, the number of lawsuits involving highway related vibration problems is increasing. In addition, the number of cases involving highway-related vibration problems decided in favor of the plaintiff has risen sharply during the aforementioned period of time. Figure AII-2 is a graphical presentation of the 19 adjudicated cases. Even though the sample size is small, an increasing trend for both lawsuits and cases decided in favor of the plaintiff is indicated.

TABLE AII

SUMMARY OF ADJUDICATED CASES RESULTING FROM HIGHWAY RELATED VIBRATION PROBLEMS 1963-1972

Complaint Case No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Individual Action		x					x	x	x	x	x	x	x	x			x	x	
Board or Comm. Action	x		x	x	x	x									x	x			x
Private Property		x				x	x	x	x	x	x	x	x	x					x
Public Property	x		x	x	x										x	x		x	
Commercial Property																	x		
Source Within 400'	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Source Beyond 400'																			
Building Damage		x	x			x		x			x		x		x				x
Annoyance	x			x	x		x		x	x		x		x		x	x	x	
Noise Mentioned	x		x	x	x	x	x		x	x		x		x	x	x	x	x	x
Heavy Vehicles/Machinery		x	x	x			x	x	x	x	x		x	x	x	x	x		x
All Traffic	x				x	x						x						x	
For Plaintiff	x*		x						x			x	x+		x	x	x	x	x
Against Plaintiff		x		x	x	x	x	x		x	x			x					
Year	1963	1964	1965	1965	1966	1966	1968	1968	1968	1969	1969	1970	1970	1970	1971	1971	1971	1972	1972

Remarks

* The court awarded $9,210.00 to compensate for diminution of value.

\+ The court awarded $37,150.00 for damages.

TABLE AII-4

LIST OF ADJUDICATED CASES RESULTING FROM

HIGHWAY RELATED VIBRATION PROBLEMS 1963-1972

1. Mississippi State Highway Commission v. Colonial Inn, Inc., 246 Miss. 422, 149 SO.2d 851 (1963).

2. Richmond County v. Williams, 109 Ga. App. 670, 137 S.E. 2d 343 (1964).

3. Board of Education v. Palmer, 88 N.J. Super. 378, 212 A.2d 564 (1965).

4. Deaconess Hospital v. Washington State Highway Commission, 66 Wash. 2d 378, 403 P.2d 54 (1965).

5. United States v. Certain Parcels of Land, 252 F.Supp. 319 (W. D. Mich. 1966).

6. Hollywood Baptist Church v. State Highway Department, 114 Ga. App. 89, 150 S.E. 2d 271 (1966).

7. Lombardy v. Peter Kiewit Sons' Company, 266 Cal. App.2d 599, 72 Cal. Rptr. 240 (1968).

8. Northcutt v. State Road Department, 209 S.2d 710 (Fla. Appl. 1968).

9. Dennison v. State, 22 N.Y.2d 408, 293 N.Y.S.2d 68 (1968).

10. Thomsen v. State, 284 Minn. 468, 170 N.W.2d 575 (1969).

11. Bassham v. Shreveport Transit Company, 227 So.2d 160 (La. App. 1969).

12. Fleetwood Synagog, Inc. v. State, 60 MISC.2d 326, 302 N.Y.S. 2d 898 (Ct. Claims 1970).

13. Reymond v. State Highway Department, 255 La. 425, 231 S.2d 375 (1970).

14. Cheek v. Floyd County, 308 F. Supp. 777 (N.D.Ga. 1970).

15. State v. Board of Education, 116 N.J. Super. 305, 282 A.2d 71 (1971).

16. City of Yakima v. Dahlin, 5 Wash. App. 129, 485 P.2d 628 (1971).

17. Bronxville Palmer, Ltd. v State, 36 A.D.2d 10, 318 N.Y.S. 2d 57 (1971).

18. People, Department of Public Works v. Volunteers of America, 98 Cal. Rptr. 423 (Cal. App. 1972).

19. New Jersey v. Board of Education, 3 E.R.C., 1159 (1972).

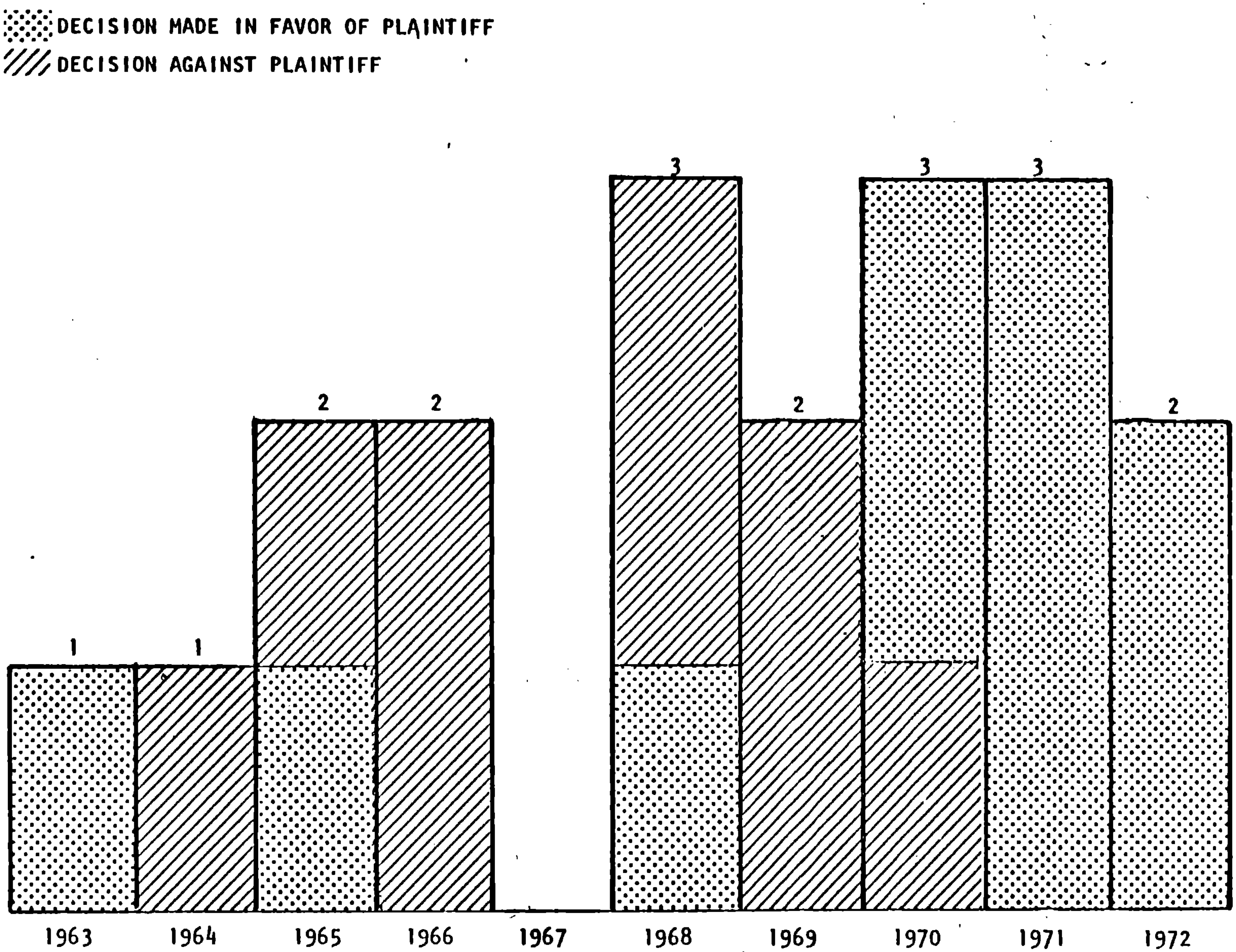


FIGURE AII-2. ADJUDICATED CASES RESULTING FROM HIGHWAY RELATED VIBRATION PROBLEMS: 1963-1972

acoustics & vibration associates

A Division of Science Applications, Inc.

2700 cumberland parkway, n.w.
suite 335
atlanta, georgia 30339
(404) 435-4461

November 15, 1974

Mr. Paul A. Wiatrak
City Engineer
Room 910
Municipal Building
Seattle, Washington 98104

Subject: U. S. Department of Transportation, Federal Highway Administration Contract DOT-FH-11-8494, subject: "Determination of Impact from Vibrations Related to Highway Use"

Dear Mr. Wiatrak:

Last week I talked by telephone with a representative of your office, Mr. M. D. Hilliard, concerning the subject contract research study which our firm is conducting for the Federal Highway Administration. I called to request the assistance of the City of Seattle with respect to one phase of this study program, and it was suggested that I write to you.

Specifically, we would like to receive information concerning street and road vibration complaints. We felt that Seattle would be a representative city to provide helpful data related to road or street vibrations that impact on adjacent building structures. Information concerning these problems would be meaningful to this contract study. Let me explain briefly the purpose and scope of our study.

This program is designed to collate and assess the physical as well as behavioral and legal literature on vibrations from highways, construction, blasting, etc., in order to authoritatively define the vibration problems for highways. The results of our effort will be the development of design guidelines to establish the impact of highway vibrations, and will be aimed at providing highway planners and design engineers with techniques to estimate and evaluate any potential vibration impact.

The main objectives of this research work are: (1) to clarify the nature and extent of the highway-induced vibration problem by improving the understanding of vibration excitation, propagation and effects, and (2) to develop guidelines to preclude or control environmental vibrations, devoting special attention to the highway vibration situation resulting in complaints or litigation.

Science Applications, Inc. / 1200 Prospect St., La Jolla, Calif. 92037

Accordingly, to help us with the complaint assessment phase of this study, we wish to request your assistance in determining occurrences and nature of complaints or litigation related to environmental vibration generated by highways, highway construction and blasting impacts, and other vibration sources. The program is equally concerned with vibration effects on structures and humans. We will use this information internally to define the problem of highway-induced vibrations relative to the practical problems encountered by highway designers and engineers.

We would like to receive any information you can furnish concerning instances or situations involving complaints and/or litigation of record in Seattle related to the highway vibration problem. We would appreciate any information you can send us, including the name and location of the project, a description of the physical situation at the project site that prompted complaint, who was the complainant, nature of the complaint, litigation related to the complaint and outcome of litigation, if any. Other information which you feel would be meaningful in developing design guidelines for use by highway planners and engineers in assessing the impact of vibrations for future highway projects will be appreciated.

Enclosed are two sample copies of the forms used by the City of Atlanta, Georgia, to record citizen complaints and document the action taken. One form records the complaint and condition at the site, and the other form is a work order authorization to repair the condition, and record time and materials. I. you can provide similar information concerning cases in Seattle, it will be most useful in our contract study. Also, an indication of the number of annual vibration complaints in Seattle in recent years will be helpful.

Thank you for your assistance in this matter.

Very truly yours,

ACOUSTICS & VIBRATION ASSOCIATES (AVA)

M. Lewis MacIntyre
Director of Development

MLM:mc

Enclosures

SAMPLE RESPONSE PAGE 1

12-9-74

CITY OF SEATTLE

DEPARTMENT OF ENGINEERING

PAUL A. WIATRAK, CITY ENGINEER

MEMBER, BOARD OF PUBLIC WORKS

Wes Uhlman, Mayor

Seattle Municipal Building, Room 910
600 Fourth Avenue, Seattle, Washington 98104

December 2, 1974

Mr. M. Lewis McIntyre
Director of Development
Acoustics & Vibration Assoc.
2700 Cumberland Parkway Northwest
Suite 335
Atlanta, Georgia 30339

Dear Mr. McIntyre:

Our file on traffic generated vibration complaints goes back to 1949. Since that time we have had just ten recorded incidences of this type of problem, although, of course, some of the problems resulted in a number of individual complaints. For your convenience, here is a synopsis of each of the ten cases.

1. On May 31, 1949, Mr. G. M. Drolesbaugh, 3514 Southwest Manning Street, wrote to complain that his house shakes when the bus goes by the intersection of 36th Avenue Southwest and Southwest Manning Street, even after City crews had repaired a concrete panel at that location. Our investigation led us to conclude that the vibrations were due in large measure to the fact that the house sits on fill material. We informed Mr. Drolesbaugh that there was nothing we could do.

In the fall of 1961, Mrs. Walter Noyes, 3702 36th Avenue Southwest (just across the street from Mr. Drolesbaugh) wrote to complain about the same problem. Our answer to Mrs. Noyes indicated that we had replaced another broken concrete panel in the intersection in 1960 and had found no voids under the pavement at that time. We also drilled two rows of test holes 3 feet on center for 70 feet and found no voids. We attributed the problem to exceptionally soft ground in the vicinity, but had no solution to offer.

On May 5, 1965, Mrs. Noyes joined 33 other residents in the vicinity in presenting a petition to the City Council, blaming the problem on voids and asking the Council to direct us to take proper remedial action. We drilled two test holes while Mrs. Noyes watched. We enountered no voids but did encounter a wet sand cushion at a depth of 6 feet. We replaced two more concrete panels. We have no record of any subsequent complaints nor of any litigation.

2. On July 10, 1950, Mrs. Harriet Gates, 2122 Dexter Avenue North, wrote to complain that her house gets badly shaken by passing traffic, particularly City buses. She thought that spring water from the hillside above might have been causing pavement damage. Our answer merely confirmed that some repair was necessary and that we would do it. There has been no subsequent correspondence.

3. In the spring and summer of 1963, some residents in the 1600 through 1800 blocks of East Lynn Street complained that trucks belonging to Fiorito Brothers Construction Company were causing house vibrations. The trucks were tractor-trailer combinations carrying approximately 18 tons of fill material from South Norfolk Street to a fill in the Montlake area. Mr. Frank Neumann, seismologist (now deceased) for the University of Washington conducted tests in the vicinity with a portable seismograph on December 10, 1963. (Mr. Neumann was acting as a expert for Fiorito Brothers, who apparently were the defendents in a court action to which the City was not a party.) He concluded that none of the measured vibrations would ordinarily be considered of damaging magnitude. His report did go on to point out that a weak vibration may accelerate the occurrence of damage which is primarily due to other causes; in this case, he surmised, the buildings damaged were already in a state of strain, most likely from settling. He did concede that the Fiorito trucks set up between 2 and 3 times the amount of vibrations generated by ordinary heavy traffic including City buses.

In the summer of 1964, we received a vibration complaint from Mr. Lloyd Hargreaves, 1806 East Lynn Street. We found little or no defect in the street surface at that time, but promised to consider the street for resurfacing the following year. We eventually resurfaced the street in 1967. We have no record of any subsequent complaints. Since the City was not a party to the aforementioned action, we don't know how it came out or if it even went to trial.

4. On March 30, 1965, Mr. D. R. Ripley, 1320-24 Queen Avenue North, wrote to complain about bus and truck vibrations and a badly cracked street surface. We drilled 12 test holes and found no voids. In July of 1965, we resurfaced the street with a two-inch asphalt lift. There have been no subsequent complaints of record.

5. In January of 1969, we received a number of complaints alleging damage to homes caused by vehicles crossing the 15th Avenue Northeast Bridge (at Northeast 105th Street). We hired the firm of Geo-Recon, a subsidiary of Shannon & Wilson, Inc., to measure vibrations at the affected homes. Geo-Recon's report, a copy of which is attached, indicated that the vibrations could not have caused the damage.

Because the vibrations were in the "clearly perceptible" range, we did take steps to reduce the vibrations, including expansion joint rehabilitation and bridge deck resurfacing with an asbestos asphalt mix in the fall of 1969.

Despite our efforts we continued to receive complaints, including one from Dr. R. A. Dimond at 10415 15th Avenue Northeast on December 12, 1969, and one from W. J. Davis at 1234 Northeast 104th Street on March 4, 1970. Following these complaints we asked the transit system to direct their drivers to slow to 20 miles per hour while crossing the bridge. This they did on June 30, 1970.

Because these later complaints suggested that the greatest and continuing source of the problem was in the south bridge approach rather than the bridge itself, we also repaired some chuck holes at that location on April 3, 1970. We have no record of any subsequent complaints.

6. On December 31, 1971, Mr. Jack Yoshikawa, owner of a 20 unit apartment building at 2700-10 Alki Avenue Southwest, wrote to complain about traffic vibrations dating back to April of that year. Mr. Yoshikawa pointed out that the timing coincided with street excavation for a large storm drain construction project on Alki Avenue Southwest. After an exchange of letters with Mr. Yoshikawa, we drilled three cores in front of the apartment building but found no voids. Examination of the street surface showed no loose slabs or sharp bumps that would be likely to cause vibrations in the apartment house. Department personnel were unable to feel any vibrations when heavy trucks or buses drove by.

Mr. Yoshikawa was still not satisfied, saying that the test did not duplicate actual conditions and that our instrument was not sensitive enough. On June 12, 1972, we told Mr. Yoshikawa that we would conduct no more tests. He wrote twice after that, the last time on February 21, 1973, hinting at the possibility of legal action. We have heard nothing more from him since then. We have received no complaints from any other source, even Mr. Yoshikawa's tenants, regarding vibrations at this location.

7. On May 2, 1973, fourteen petitioners living at nine different addresses in the 2400 block of Alki Avenue Southwest and the 2500 block of 56th Avenue Southwest (which intersects Alki Avenue Southwest) wrote to complain of vibrations caused by buses traveling at certain speeds. The letter indicated they had had dealings with the Engineering Department on this subject in the spring of 1972, but we can find nothing in writing.

As in the Yoshikawa case (No. 6 above) the petitioners attributed the trouble to storm drain construction. We drilled seven four-inch cores in the pavement on Alki Avenue Southwest, east and west of its intersection with 56th Avenue Southwest. Five of the cores were drilled over the storm drain, and the other two in the center lane the buses normally travel in. We found no voids. The sand subgrade appeared to be adequately compacted. The Building Department examined the subject buildings for structural damage and found none. (Two of the buildings had hairline cracks that could have been caused by traffic vibrations.)

Not satisfied with our response, the lead petitioner, Mr. Larry Rouvelas, 2430 Alki Avenue Southwest, petitioned the Mayor for assistance. However, the Mayor concurred in the Engineering and Building Department responses, and suggested the petitioners consider retaining a soils engineer to document the extent of the problem for possible court action. Finally, on September 14, 1973, the Transit System agreed to instruct their drivers to reduce speed when operating on Alki Avenue Southwest between 55th Avenue Southwest and 57th Avenue Southwest. This is the last we have heard of this problem.

8. On February 27, 1974, Mrs. G. M. Kovacevich, 3421 Rainier Avenue South, wrote complaining about exterior and interior cracks allegedly due to vibrations resulting from the use of heavy equipment and jack hammering during the resurfacing of Rainier Avenue South in the summer of 1973. As this was a Washington State Highway Department project, we referred her letter to that agency for action. We are not aware of the outcome; if you wish further information please write to Mr. E. I. Roberts, District Engineer, State Highway Department, 10637 Northeast 8th Street, Bellevue, Washington, 98004, Attention Mr. H. J. Semenock, District Utilities Engineer.

9. On November 17, 1974, Mr. Jack Reed, 1156 Alki Avenue Southwest, owner of a four-story apartment building at that address, wrote to complain about damages from traffic vibrations dating back to last year when storm drainage was constructed at that location. Apparently Mr. Reed had verbal discussions with a representative of our office at that time. Our employee told Mr. Reed that the vibrations would probably stop when the pavement patch over the storm drain had settled fully. Mr. Reed said there has been some improvement but not enough. He cites damages including two toilets that had to be replaced, two joint leaks in kitchen pipes, and numerous plaster cracks. As the storm drain contractor's period of responsibility is still in force, this problem is currently in the hands of our Construction Division, who are investigating.

Six of the eight cases I have listed were initiated by letters from the complainants. The other two started out with phone calls and were serious enough for us to compile a file on them. It is possible, however, that other telephone complaints of this nature have been received (and hopefully resolved) but they would be filed by location along with numerous other complaints of all kinds. So it isn't feasible to try to go back and see if we have missed any.

I hope the foregoing information, along with the attached report, is helpful to you in this first phase of your study. If we can be of further assistance don't hesitate to call on us.

Yours very truly,

PAUL A. WIATRAK, P.E.
City Engineer

By M.D. Hillyard
M. D. HILLYARD
Assistant Supervisor
Street & Bridge Maintenance

MDH:pdw

APPENDIX III

LEGAL PERSPECTIVE OF TRAFFIC-INDUCED VIBRATION

This appendix presents a review of the present laws relating to highway vibration, adjudicated cases resulting from vibration, and an annotated bibliography of the legal literature concerning highway induced vibration.

Present statutes relating to highway induced vibration are classified according to the United States Code, State Codes, and relevant municipal codes. A brief discussion of related foreign laws concerning environment vibration is presented since highway induced vibration is recognized in all industrialized countries as a significant environmental problem that is becoming more serious in recent years. Conclusions are presented at the end of each section.

Adjudicated cases resulting from vibration are presented in legal context since apparently highway related vibration is treated by the courts on a case by case basis with excessive vibration from all sources being considered as equally insulting. Over 40 cases are discussed in this context. Conclusions are presented at the end of each section.

An annotated bibliography is presented that categorizes legal literature on highway vibration, environmental vibration, blasting, health and job safety, sonic booms, and noise control. The review of law related literature pertaining to noise control is presented since the legal principles are similar, if not identical, to vibration suits.

LAWS CONCERNING HIGHWAY VIBRATION

Environmental vibration, including highway vibration has not been the subject of much legislative activity in the United States. The federal Noise Control Act of 1972 focuses on measurable sound and is not concerned with inaudible vibration, or vibratory effects separable from sound. This differs from the approach of the common law courts which have always been willing to recognize vibration and noise as differing aspects of a common nuisance activity.

U. S. Statutes

The fact that courts recognize vibration as an environmental insult, which, in the appropriate case, will allow the complainant legal redress, is significant because of a number of federal statutes phrased in general terms which codify a governmental duty to protect environmental quality and to guard against adverse environmental effects. Although vibration is not mentioned in these statutes, and although no vibration cases have been decided under them, the standard of environmental quality which they provide for, would, in the proper case require the federal official to guard against excessive environmental vibration in the construction or maintenance of the project.

The first of these general statutes, which confer on the Federal Highway Administration a broad authority and duty to plan against the adverse effects of vibration, is the National Environmental Policy Act, 42 U.S.C. 4321 et seq. which states in pertinent part,

> Sec. 101.(a) The Congress, recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, high-density urbanization, industrial expansion, resource exploitation, and new and expanding technological advances and recognizing further the critical importance of restoring and maintaining environmental quality to the overall welfare and development of man, declares that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations, to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and furure generations of Americans.
>
> (b) In order to carry out the policy set forth in this Act, it is the continuing responsibility of the Federal Government to use all practicable means, consistent with other essential considerations of national policy, to improve and coordinate Federal plans, functions, programs, and resources to the end that the Nation may--
>
> (1) fulfill the responsibilities of each generation as trustee of the environment for succeeding generations;
>
> (2) assure for all Americans safe, healthful, productive, and esthetically and culturally pleasing surroundings;
>
> (3) attain the widest range of beneficial uses of the environment without degradation, risk to health or safety, or other undesirable and unintended consequences;
>
> (4) preserve important historic, cultural, and natural aspects of our national heritage, and maintain, wherever possible, an environment which supports diversity, and variety of individual choice;
>
> (5) achieve a balance between population and resource use which will permit high standards of living and a wide sharing of life's amenities; and
>
> (6) enhance the quality of renewable resources and approach the maximum attainable recycling of depletable resources.
>
> (c) The Congress recognizes that each person should enjoy a healthful environment and that each person has a responsibility to contribute to the preservation and enhancement of the environment.

Sec. 102. The Congress authorizes and directs that, to the fullest extent possible: (1) the policies, regulations, and public laws of the United States shall be interpreted and administered in accordance with the policies set forth in this Act, and (2) all agencies of the Federal Government shall--

(A) utilize a systematic, interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts in planning and in decisionmaking which may have an impact on man's environment;

(B) identify and develop methods and procedures, in consultation with the Council on Environmental Quality established by title II of this Act, which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in decisionmaking along with economic and technical considerations;

(C) include in every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment, a detailed statement by the responsible official

(i) the environmental impact of the proposed action,

(ii) any adverse environmental effects which cannot be avoided should the proposal be implemented,

(iii) alternatives to the proposed action,

(iv) the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity, and

(v) any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented.

Prior to making any detailed statement, the responsible Feder_: official shall consult with and obtain the comments of any Federal agency which has jurisdiction by law or special expertise with respect to any environmental impact involved. Copies of such statement and the comments and views of the appropriate Federal, State, and local agencies, which are authorized to develop and enforce environmental standards, shall be made available to the President, the Council on Environmental Quality and to the public as provided by section 552 of title 5, United States Code, and shall accompany the proposal through the existing agency review processes;

(D) study, develop, and describe appropriate alternatives to recommended courses of action in any proposal which involves unresolved conflicts concerning alternative uses of available resources;

The mandate of NEPA, to the Highway Administration among other government agencies, to assess and avoid adverse environmental consequences where possible, is reinforced by the Federal Highway Act, which states, in pertinent part (23 U.S.C. 109h),

(h) Not later than July 1, 1972, the Secretary, after consultation with appropriate Federal and State officials, shall submit to Congress, and not later than 90 days after such submission, promulgate guidelines designed to assure that possible adverse economic, social, and environmental effects relating to any proposed project on any Federal-aid system have been fully considered in developing such project, and that the final decisions on the project are made in the best overall public interest, taking into consideration the need for fast, safe and efficient transportation, public services, and the costs of eliminating or minimizing such adverse effects and the following:

(1) air, noise, and water pollution;

(2) destruction or disruption of man-made and natural resources, aesthetic values, community cohesion and the availability of public facilities and services;

(3) adverse employment effects, and tax and property value losses;

(4) injurious displacement of people, businesses and farms; and

(5) disruption of desirable community and regional growth.

Such guidelines shall apply to all proposed projects with respect to which plans, specifications, and estimates are approved by the Secretary after the issuance of such guidelines.

The action enforcing provisions of the National Environmental Policy Act, calling for the preparation of an environmental impact statement, require the Administrator to analyze and assess all significant environmental consequences of the project. The policy behind this procedure is to avoid adverse effects. The Federal Highway Administration's regulations, codified as 23 Code of Federal Regulations, Appendix A, Environmental Impact Statements, Paragraph 4, state,

4. Policy. It is a national policy that all Federal agencies promote efforts for improving the relationship between man and his environment and to make special effort for preserving the natural beauty of the countryside and public park and recreational lands, wildlife and waterfowl refuges, and historic sites. It is also national policy that Federal agencies consult with other appropriate Federal, State, and local agencies; assess in detail the potential environmental impact in order that adverse effects are avoided and environmental quality is restored or enhanced, to the fullest extent practicable; and utilize a systematic, interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts in planning and decisionmaking which may have an impact on man's environment. The environmental assessments include the broad range of both geneficial and detrimental effects.

Federal courts have interpreted the National Environmental Policy Act in more than 400 lawsuits. It is not a paper tiger; if the court finds that the agency in question has not complied with the Act (either by ignoring or failing to adequately evaluate the environmental consequences of the proposal and its alternatives) it will enter an order enjoining action until the Act has been complied with. Although no NEPA case has ever been decided on the basis of highway vibration, it is the sort of adverse environmental effect which must be assessed under the statute.

Certain historical preservation districts receive special protection by federal statutes; 16 U. S. C. 470f states,

> § 470f. Effect of Federal undertakings upon property listed in the National Register; comment by Advisory Council on Historic Preservation
>
> The head of any Federal agency having direct or indirect jurisdiction over a proposed Federal or federally assisted undertaking in any State and the head of any Federal department of independent agency having authority to license any undertaking shall, prior to the approval of the expenditure of any Federal funds on the undertaking or prior to the issuance of any license, as the case may be, take into account the effect of the undertaking on any district, site, building, structure, or object that is included in the National Register. The head of any such Federal agency shall afford the Advisory Council on Historic Preservation established under sections 470i-470n of this title a reasonable opportunity to comment with regard to such undertaking.

The Federal Highway Administration's regulations reprinted at 23 Code of Federal Regulations, Appendix A, Procedures for Historic Preservation, state, in pertinent part,

> PROCEDURES FOR HISTORIC PRESERVATION
>
> 1. The provisions of 16 U.S.C. 470(f) require that all proposed highway sections that are federally assisted be developed with consideration to effected districts, sites, buildings, structures, or objects that are included in the National Register for Historic Preservation. This authority derives from Section 106 of the National Historic Preservation Act. Procedures for compliance have been implemented by the Advisory Council on Historic Preservation, and the National Park Service, Department of the Interior, as follows:
>
> a. At the earliest stage of planning or consideration of any undertakings carried out, licensed, or financially assisted by the Federal Government, the HA and FHWA should follow these steps:

(1) Consult the National Register of Historic Places to determine if a National Register property is involved in the undertaking. The National Register is maintained by the Office of Archeology and Historic Preservation, National Park Service, and monthly addenda are published in the Federal Register.

(2) Apply the "Criteria for Effect." If there is no effect, the undertaking may proceed. (See paragraph 3 of this appendix.) This determination of effect should be made by the HA in consultation with the division engineer, the State Liaison Office and a representative of the Office of Archeology and Historic Preservation. If there is documented agreement that a project will not have an effect on the National Register Historic Site, no further review is required under the National Historic Preservation Act.

(3) If there is an effect, the HA in consultation with the FHWA division engineer, State Liaison Officer[1] and a representative of the Office of Archeology and Historic Preservation of the National Park Service shall:

(a) Determine if the effect is adverse--if not, the undertaking may proceed;

(b) Upon finding an adverse effect, select and agree upon a prudent and feasible alternative to remove the adverse effect, in which case the undertaking may proceed;

(c) Failing to find and agree upon an alternative, recommend all possible planning to minimize the adverse effect and delay further processing of the undertaking pending the receipt of comments from the Advisory Council.

(4) Provide written notice affording the Advisory Council an opportunity to comment upon doubtful or unresolved situations of adverse effect and upon request submit a report of the undertaking.

2. If there is a finding of adverse effect, the proposed highway section is to be processed in accordance with these procedures and the Office of Environmental Policy should be notified and kept informed of further developments. If it becomes necessary to provide a written notice affording the Advisory Council on Historic Preservation an opportunity to comment in doubtful or unresolved situations of adverse effect, the Office of Environmental Policy will act as the coordinating element for the FHWA.

3. Criteria for effect. a. A federally financed or licensed undertaking shall be considered to have an effect on a National Register listing (districts, sites, buildings, structures, and objects, including their settings) when any condition of the undertaking creates a change in the quality of the historical, architectural, archeological, or cultural character that qualified the property under the National Register criteria for listing in the National Register.

b. Generally, adverse effect occurs under conditions which include but are not limited to:

(1) Destruction or alteration of all or part of a property;

---

[1] State Liaison Officers are appointed by the Governors to be responsible for State activities under the National Historic Preservation Act.

(3) Introduction of visual, audible, or atmospheric elements that are out of character with the property and its setting (i.e. introduction of a new highway or a higher type functional highway, such as a freeway for an arterial, into the environment of a historic site).

Obviously, noticeably prolonged and intense vibration would come within the ambit of the criteria for effect, and would bring section 470(f) into action.

The Federal Highway Administration regulations promulgated pursuant to the Noise Control Act and published at 23 Code of Federal Regulations Part 772 are aimed to quieten highway noise; however, the regulatory prescriptions (acquisition of buffer zones, construction of noise barriers) would also serve to dampen vibration effects. In order to be eligible for Federal aid participation, all projects to which the noise standards apply, are to include noise abatement measures designed to meet design noise levels in federal standards.

Currently, there are no federal statutes governing vibration in the workplace such as those found in Czechoslovakia. There are indications that the Occupational Safety and Health Administration is studying action in this area (See Lehmann, P., "Vibration," Job Safety & Health, January 1974, pp. 5-12), but no regulations appear to be forthcoming in the near future. The physiological effects of vibration, whether from environmental sources such as highways or from machinery in the workplace, have not received much attention in the United States. Our courts and lawmakers, however, have been concerned with the property damage caused by extended vibration.

<u>State Laws</u>

State statutes have ignored vibration up until this year's legislative sessions, when three states, Connecticut, Kentucky, and Maryland enacted similar provisions based on the Council of State Government's suggested State Noise Control Act, which was drafted by workshop participants at the Second National Symposium on Environmental Legislation in 1973. This model statute does not attempt to regulate vibration specifically, but expands the definition of noise to include vibration. Section 103 (Definitions) states in pertinent part,

> "(4) "Noise" means the intensity, frequency, duration, and character of sounds from a source or number of sources. Noise includes vibrations of sub-audible frequency."

The Connecticut statute (reprinted in Bureau of National Affairs' Noise Regulation Reporter 81:3901) states,

> Section 26(e): "Noise" means the intensity, frequency, duration and character of sounds from a source or number of sources. Noise includes vibrations of subaudible or superaudible frequency."

The Kentucky statute reprinted at Section 81:5421 of the Noise Regulation Reporter is identical to the Council of State Government's suggested statute.

The Maryland statute reprinted at section 81:5701 of the Noise Regulation Reporter states,

> 823(e) "Noise" means the intensity, frequency, duration, and character of sound. Noise includes sound and vibration of sub-audible frequencies."

This type of statute appears to address itself to the problem of highway vibration. Since all three statutes are new, there has been no litigation or enforcement activity concerning them.

Municipal Ordinances

While many cities have passed ordinances regulating noise, relatively few have enacted laws governing vibration. Of those jurisdictions which have dealt with the problem, the majority have.provisions in their zoning codes dealing with vibration, none of which appear to be broad enough to deal with highway vibration.

The simplest type such as the protective Zoning Bylaw of Acton, Massachusetts resembles a classic nuisance ordinance:

> " 1. *Performance Standards* -- No land or building shall be used or occupied in any manner as to create any dangerous, injurious, noxious or otherwise objectionable fire, explosion, radioactive or other hazard, noise or vibration: smoke, dust, odor or other form of air pollution; electrical or other disturbance; glare, liquid or solid refuse or wastes. "

The Fort Lauderdale, Florida Zoning Code (Industrial) states,

> " Sec. 47-78.1. Uses prohibited. -- The uses prohibited in B-3 district shall be as follows:
> (a) The use of any portion for open storage without 5-foot concrete wall in the rear and on the side of said site.
> (b) Any industry or business which is obnoxious because of dust, dirt, smoke, fumes, odors, noises, vibrations, radioactive waves or dangerous hazards.
> (c) Any use not specifically permitted in section 47-78. (Ord. No. C-1126, § 4, 5-17-55)
> Fort Lauderdale Industrial Air Park.
> Article VIII-B. "M-1-A" District.
> Sec. 47-81.1. Purpose of district.
> The purposes of the M-1-A zone is to govern all uses of land offered for sale within the boundaries of the Fort Lauderdale Industrial Air Park as they are not existing

or may be hereafter set. The M-1-A Industrial Zone is to assure that industrial development will not have an undesirable effect because of smoke, sound, dust, dirt, noxious gases, odor, vibration, heat, or electromagnetic interference. (Ord. No. C-1968 § 1, 10-29-63; Ord. No. C-66-46, § 1, 8-2-66) "

Section 5 of the New Orleans Zoning Ordinance titled "Exceptions and Modifications to Use Regulations" declares,

> " Power plants, heating or refrigerating plants or apparatus or machinery not a part of the main building, which are accessory to permitted uses in the A-Single Family District, B-Two Family District. C-Four Family District, D-Multiple Family District, M-1 and M-2 Medical Service Districts and in the H-1 Vieux Carre Residential District, shall be permitted in the buildable area or required rear yards of the above-named districts only if so placed and operated as to cause the least inconvenience to owners or tenants of adjoining lots and buildings; and provided that all of the above-mentioned activities comply with existing city ordinances and do not cause serious annoyance or injury to occupants of adjoining premises by return of the emission of odors, fumes or gases, dust, smoke, noise or vibration, light or glare, or other nuisances. "

The most detailed city vibration law is found in sections 17-4.15 to 17-4.19 of the Chicago Noise Ordinance:

> " 17-4.15 Any property use established in a Manufacturing Comme-·ial, or Business Zoning District shall be so operated as to comply with the performance standards governing vibration set forth herein for the Zoning District in which such use shall be located.
>
> 17-4.16 In M1-1 to M1-5 Restricted Manufacturing Zoning Districts inclusive, any use or portion thereof creating earth-shaking vibrations such as are created by drop forges or hydraulic surges shall be controlled in such manner as to prevent transmission beyond the lot lines of earth-shaking vibrations perceptible without the aid of instruments, except for lot lines adjoining an M3 Heavy Manufacturing Zoning District but in no case shall any such vibration be allowed to create a nuisance or hazard beyond the lot lines.
>
> 17-4.17 In M2-1 to M2-5 General Manufacturing Zoning Districts inclusive, any use or portion thereof creating intense earth-shaking vibrations such as are created by drop forges, or heavy hydraulic surges, shall be set back at least 300 feet from the boundary of a Residence, Business, or Commercial Zoning District and at least 150 feet from the boundary of an M1 Restricted Manufacturing Zoning District, unless such operation is controlled in such a manner as to prevent

transmission beyond the lot lines of earth-shaking vibrations perceptible without the aid of instruments.

17-4.18 In M3-1 to M3-5 Heavy Manufacturing Zoning Districts, inclusive, the performance standards governing vibration in the M2 Zoning Districts shall apply.

17-4.19 In Business and Commercial Zoning Districts, the performance standards governing vibration in the M1 Zoning Districts shall apply. "

Only a few cities attempt to define objective criteria for measurement of objectionable vibration. Supplementary ordinance .7003 of Peoria, Illinois states,

.7003. Vibrations.--Vibrations shall be measured at any adjacent lot line and/or district boundary as indicated. At the specified points of measurement, the vibrations shall not exceed the limits listed. The instrument used for these measurements shall be a three component measuring system.

Particle velocity as specified may be measured directly or if computed on the basis of displacement and frequency measurements shall be computed from the formula 6.28 FD where F is the frequency and vibrations per second and D is the single amplitude displacement of the vibration in inches. The following page contains a nomogram of the formula--particle velocity equals 6.28 FD and it may be used to determine the appropriate particle velocity.

For the purpose of this Ordinance, steady state vibrations are vibrations which are continuous (such as a printing press) or vibrations in discrete impulses more frequent than one hundred per minute (such as an air compressor). Discrete impulses which do not exceed 100 per minute shall be considered as impact vibrations (such as a drop hammer).

The Columbus, Ohio Zoning Code includes the following provision:

Zoning Code: Ch. 3343

3343.11 Noise, seismic effects and particulate matter; performance standards for EQ Excavation and Quarrying Districts.--

(a)(1) As measured at any street or other property line, the maximum sound intensity resulting from blasting or drilling shall not exceed one hundred decibels.

(2) The quantity of explosive in any primary shot shall be controlled to prevent damage to any structure of normal construction or to avoid creation of a nuisance to surrounding property and shall not exceed that specified in the following table:

Distance from blast area to nearest structure, neither quarry owned nor quarry leased (in feet)	Maximum quantity of explosives per shot for instantaneous firing or per delay for delay firing in pounds	
	Normal overburden	Abnormal overburden
100[1]	340	70
200	420	78
300	525	100
400	635	125
500	800	160
600	950	200
700	1,175	245
800	1,500	300
900	1,830	360
1,000	2,250	430
1,200	3,500	610
1,400		820
1,600		1,250
1,800		1,900
2,000		3,000

[1]Minimum allowable distance when approved missile protection methods are used.
[2]More than 50 feet to bedrock.

(3) When ground frequency and displacement in relation to the quantity of explosive in a primary blast can be determined by approved instrumentation, such blast shall be controlled in accordance with the maximum allowable amplitudes of ground vibration in relation to vibration frequency specified in the following table:

Table of frequency.--Amplitude relations frequency of maximum amplitude ground motion in cycles per second inches

Up to 10	Not more than	0.0305
20		0.0153
30		0.0102
40		0.0076
50		0.0061
60		0.0051

Several cities provide subjective tests for measurement of objectionable vibration, such as Article 612, Zoning District Regulations of the Denver City Code states,

"Article 612-Zoning District Regulations
(Portion Pertaining to Noise Only)
District: R-0, R-1, R-2, R-2-A.

Volume of Sound Generated.--Every use, unless expressly exempted by this ordinance, shall be so operated that the volume of sound inherently and recurrently generated does not exceed fifty-five decibels at any point of any boundary line of the Zone Lot on which the use is located.

Vibration Generated.--Every use shall be so operated that the ground vibration inherently and recurrently generated is not perceptible, without instruments, at any point of any boundary line of the Zone Lot in which the use is located.

District: R-3, R-4, B-1, B-2, I-P, I-0, R-3-X, B-A-1, B-A-2, R-5.

Volume of Sound Generated.--Every use, unless expressly exempted by this ordinance, shall be so operated that the volume of sound inherently and recurrently generated does not exceed sixty decibels at any point of any boundary line of the Zone Lot on which the use is located.

Vibration Generated.--Every use shall be so operated that the ground vibration inherently and recurrently generated is not perceptible, without instruments, at any point of any boundary line of the Zone Lot on which the use is located.

District: RS-1, RS-2, RS-3, RS-4.

Volume of Sound Generated.--Every use, unless expressly exempted by this ordinance, shall be so operated that the volume of sound inherently and recurrently generated does not exceed sixty-five decibels at any point of any boundary line of the Zone Lot on which the use is located.

Vibration Generated.--Every use shall be so operated that the ground vibration inherently and recurrently generated is not perceptible, without instruments, at any point of any boundary line of the Zone Lot on which the use is located.

District: B-3, B-4, B-5, B-6, I-0, B-8, B-A-3, B-A-4.

The Tucson, Arizona City Code deals with vibration in its Planning and Zoning section which declares,

"Sec. 23-391(22). Vibration: No vibration shall be permitted which is discernible beyond the lot line to the human sense of feeling for three minutes or more duration in any one hour of the day between the hours of 7:00 a.m. to 7:00 p.m., or of thirty seconds or more duration in any one hour during the hours of 7:00 p.m. and 7:00 a.m.

Foreign Laws

During recent years, the most intense legal activity concerning regulation of vibration has been in East European countries such as the Soviet Union and Czechoslovakia, where the focus has been on the physiological consequences of vibration in the workplace as opposed to environmental vibration from sources such as highways. The Czechoslovakian vibration law is outlined in an article, "The Czechoslovakian Hygiene Regulation on Protection Against Vibration," Kryze, B., in Work-Environment-Health, Vol. 7 No. 1, pp. 51-56, 1970. The law regulates certain types of industrial activity, setting maximum permissible values for vibration, critical frequency bands in which parts of the body are in resonance, and obligatory measures to be taken against cold and moiseture for the protection of workers exposed to vibration.

While the Czechoslovakian law on vibration focuses on the workplace, the British law, in contrast, focuses on environmental vibration and is applicable to highway induced vibration. Section One of the Noise Abatement Act of 1960 is entitled, "Noise or Vibration Nuisance" and reads,

> (1) Subject to the provisions of this section, noise or vibration which is a nuisance shall be a statutory nuisance for the purposes of Part III of the Public Health Act 1936, and the provisions of that Act shall have effect accordingly as if subsections (1) to (4) of this section were provisions of the said Part III.
> (2) In relation to noise or vibration alleged to be a statunuisance by virtue of the foregoing subsection--
> (a) section ninety-nine of the said Act of 1936 (which provides that a complaint of the existence of a statutory nuisance may be made by any person aggrieved by the nuisance) shall have effect as if for the reference to any person aggrieved by the nuisance there were substituted a reference to any three or more persons each of whom is the occupier of land or premises and is in that capacity aggrieved by the nuisance; and
> (b) section one hundred and nine of that Act (which contains a saving from the operation of the said Part III for mines and industrial processes) and sections three hundred and thirteen and three hundred and seventeen of that Act (which relate to repeals and alterations of local Acts) shall not apply.
> (3) In proceedings brought by virtue of subsection (1) of this section in respect of noise or vibration caused in the course of a trade of business, it shall be a defence for the defendent to prove that the best practicable means have been used for preventing, and for counteracting the effect of, the noise or vibration.
> (4) Without prejudice to the savings contained in Part XII of the said Act of 1936, no notice shall be served or proceedings brought by virtue of subsection (1) of this section in respect of noise or vibration caused by statutory undertakers in the exercise of powers conferred on them by any enactment or statutory order.

(5) In the application of this section to Scotland--
(a) in subsection (1) for the words from 'shall be a statutory nuisance' to the end of the subsection there shall be substituted the words 'shall be a nuisance liable to be dealt with summarily in the manner provided in Part II of the Public Health (Scotland) Act 1897, in the same way and to the same effect as in the case of a nuisance under paragraph (6) of section sixteen of that Act, and a county or town council shall have the like powers and duties in relation to such noise or vibration as they have in relation to a nuisance under that Act';
(b) subsection (2) shall be omitted, but in relation to noise or vibration alleged to be a nuisance by virtue of this section, section twenty-two of the said Act of 1897 shall have effect with the substitution for references to ten ratepayers of the district of the local authority of references to any three or more persons each of whom is the occupier of land or premises and is in that capacity aggrieved by the nuisance; and
(c) in subsection (4) for the reference to Part XII of the said Act of 1936 there shall be substituted a reference to Part XII of the said Act of 1897.

(7) Nothing in this section shall apply to noise or vibration caused by aircraft.

It should be noted that aircraft vibrations are excepted from the Act's jurisdiction, and that the defendant may escape liability by showing that he has used the best practicable means for counteracting the effect of the vibration. By making vibration a statutory nuisance, the enforcement of the national Act must be carried out on the local level, just as would a municipal nuisance ordinance. Accordingly, the British law has been criticized as being weak in its enforcement provisions.

Conclusion

No attempt has been made, either on the national or local level, to draft a comprehensive statutory scheme to regulate vibration, such as has been done with noise. Thus, control of excessive vibration has been left to private complainants using the traditional, but limited and rather ineffective, theories of nuisance and inverse condemnation. In the last few years, a series of broadly remedial statutes, such as the National Environmental Policy Act, seeking to insure environmental quality have been passed, which, theoretically, could serve as a basis for plaintiff's relief in future litigation concerning vibration.

ADJUDICATED CASES RESULTING FROM VIBRATION

The law concerning vibration is intimately involved with the law concerning noise; the two are frequently confused. But while there are many statutes regulating noise, there are few regulating vibration, and while many judicial decisions can be found on vibration, there are relatively few concerning noise. Noise is regulated by many statutes on the state and federal level, including the Noise Control Act of 1972, 42 U.S.C. # 4901-18, the language and legislative history of which suggests that it is inapplicable to vibration (inaudible shaking as opposed to audible sound). A review of state statutes reveals that the legislative focus has been on audible sound waves, as opposed to inaudible vibration. A few city ordinances address the problem of excessive vibration, but in most jurisdictions the problem is relegated to the courts, where the law of vibration is made on a case by case basis.

The common law courts, which have given little sympathy to noise claims, have recognized excessive vibration as an insult which may be redressed by a number of traditional legal remedies such as nuisance or inverse condemnation. These cases are the results of conventional private litigation and seldom are colored by environmental considerations. In most instances, these traditional cases have been brought by aggrieved plaintiffs whose property has been damaged by concussions from explosive blasting activity or sonic booms or by prolonged vibrations from a nearby generator, highway, or railroad.

The adjudicated cases concerning highway departments have arisen out of two different types of activities: (1) construction, with its blasting and pile driving, and (2) operations, with complaints based on vibrations from increased traffic. Some of the peculiarities of these cases are discussed below, together with a discussion of non-highway vibration cases arising out of analogous activities such as operation of a railroad, and cases not related to highways, but involving vibration, arising out of sonic booms and activities carried on with explosives.

The Constitutional Requirement of Compensation: "Taking" and "Damaging" Clauses

Suits brought by property owners against the highway department or other governmental agencies responsible for highway construction or operation are usually based on a provision of the state constitution which parallels the takings clause of the Fifth Amendment of the Federal Constitution which states, ". . .nor shall private property be taken for public use, without just compensation." State constitutions, as a matter of course, reenact on a state level the federal takings guarantee; but many states have gone beyond the federal takings clause and provide for compensation to property owners whose land is damaged, but not taken.

Comparison of two cases, one from a state, Ohio, with a "takings" clause, the other from a state, Georgia, with a "damages" clause, illustrates the difference in practice. In State ex rel Fejes v. City of Akron, 2 Ohio App.2d 57, 206 N.E.2d 418 (1965), the court held that the city was not liable for damage caused by vibrations resulting from highway construction activity adjacent to the plaintiff's property because there was no actual "taking" of his land by the government. The Ohio constitutional provision provided for compensation for governmental takings only in the literal sense, that is actual physical expropriation. In contrast, the Georgia constitution, Art. I, Sec. III, Para. I of the Constitution of 1945 (Code Ann. #2-301), provides that,

> "Private property shall not be taken, or damaged, for public purposes, without just and adequate compensation being first paid," (Emphasis added.),

and, in Richmond County v. Williams, 109 Ga. App. 670, 137 S.E. 2d 343 (1964), the court held that the plaintiff landowner should receive compensation for the cracks in his ceilings, walls, floors, windows and doors directly damaged by highway construction being carried on fifty feet away from his land even though no portion of his property had been taken for the project.

While Georgia courts will award compensation for physical damage, they have so far drawn the line on allowing recovery for elements of inconvenience such as noise and annoying vibration. In the Richmond County case, additional recovery was denied to the plaintiff for claims based on annoyance growing out of horn blowing, glare of lights, and increased traffic. Indeed, a Georgia court has held that the increased noise, smoke, and dust from highway construction which did not result in actual physical damage to the plaintiff's home, did not create a permanent decrease in property value, and hence no recovery was possible. See Hollywood Baptist Church v. State Highway Dept., 114 Ga. App. 89, 150 S.E. 2d 271 (1966). Similarly, in Reymond v. State Dept. of Highways, 255 La. 425, 231 S.2d 375 (1970), the court awarded damages to the plaintiff for the visible damage caused by pile driving activity in construction of a highway on neighboring land. The plaintiff's recovery was measured by the decrease in the market value of her house caused by structural damage attributable to vibration from pile driving.

In Lombardy v. Peter Kiewit Sons' Co., 266 Cal. App.2d 599, 72 Cal. Rptr. 240 (1968), the plaintiff did not allege property damage, but did aver that the nearby highway construction caused mental, physical and emotional stress resulting from noise, dust, and vibration. The court held that the plaintiff did not state a case in inverse condemnation without alleging substantial damage to property.

Although approximately half of the states have a "damaging" provision as well as a "taking" clause, legal commentators believe that decisions from jurisdictions with a "takings" clause only can be just as liberal. They cite cases such as Eaton v. Boston, C. & M. R. R., 51 N.S. 504 (1872), in which the New Hampshire Supreme Court awarded compensation to a plaintiff whose property had been flooded by water coming through a cut made for a railroad track. The court got around the constitutional limitation of New Hampshire's constitution which limits compensation to governmental takings by holding that the right to property includes the right to beneficial use, and that when a public project interferes with that use, as in the Eaton case, the property had been "taken" and compensation must be made. Although courts in some states evade the full force of the absence of a "damaging" clause by such a rationale, the job of the plaintiff's lawyer and the judge seeking to award a recovery to the injured landowner is easier if the law forthrightly, by means of a "damaging" clause, permits recovery for consequential damages such as vibration. See Spies and McCoid, "Recovery of Consequential Damages in Eminent Domain, 48 Va. L. Rev. 437, 443 (1962).

A modern application of this principle is found in Board of Education v. Palmer, 88 N. J. Super. 378, 212 A.2d 564 (1965), where the plaintiff school board was held entitled to an award, even though there was no physical taking, if it could show that the beneficial use of the school grounds would be impaired during the course of highway construction because of danger, noise, and construction activity. Similarly, in City of Yakima v. Dahlin, 5 Wash. App. 129, 485 P.2d 628 (1971), the plaintiff was allowed to sue for the diminution in the value of his property caused by the noise and other annoying side effects resulting from highway construction, even though there was no physical taking. See also Bronxville Palmer, Ltd. v. State, 36 A.D. 2d 10, 318 N.Y.S. 2d 57 (1971).

Tangible versus Intangible Damages

Vibration may be extremely annoying to the plaintiff, yet not rise to the level of environmental harm for which the court will award relief. Inconvenience does not of itself constitute the kind of "damage" contemplated by the eminent domain and inverse condemnation laws, unless the plaintiff can show that he has suffered "special damages" different in kind and degree from those suffered by the public at large. See Northcutt v. State Road Dept., supra; Richmond County v. Williams, supra; Reymond v. State, supra. Evidence of physical injury to the plaintiff's property always makes his suit easier since there is a long line of cases in which awards have been given to compensate for tangible damage resulting from highway vibration. See Richmond County v. Williams, supra; Northcutt v. State Road Dept., 209 S.2d 710 (Fla. Appl. 1968). It is much easier to argue that property has been "taken" or "damaged" if it has suffered visible physical injury.

Highway Construction

Vibration and concussion damage cases arising out of blasting activity have been the subject of much legal commentary. Dean Prosser notes, in Prosser, Law of Torts, 4th ed., West Publishing Company, St. Paul, at page 513, that blasting has run the gamut of all possible theories of liability. The courts of a number of states have held that blasting is an ultrahazardous activity, and that the perpetrator of the excessive vibrations will be held liable, whether negligent or not; while the courts of other states, require the complainant to show that the work was carried on in a negligent manner. A review of the different position taken by various state courts can be found in 20 American Law Reports, Annotated, Second Series, "Annotation: Liability for Property Damage by Concussion from Blasting" The Lawyers Co-operative Publishing Company, Rochester (1951) at 1372. Cases arising out of highway blasting incidents have often applied the latter standard requiring proof of negligence on the part of the contractor. The court in Watson v. Mississippi River Power Co., 174 Iowa 23, 156 N.W. 188 (1916) rationalized this different treatment on the ground that highway construction is carried out under the authority of the state. However, in the appropriate case, courts will not hesitate to assess damages against the blasting contractor at work on a public project. In H. L. Butler & Sons v. Walpole, 239 S.W.2d 653 (Tex. Cir. App. 1951), the court held that the contractor would be liable for any damage caused by concussions and debris resulting from highway construction activities if such damages resulted from the contractor's negligence or failure to take precautions. Texas courts have spoken out more frequently on this issue than the courts of other states. In Standard Paving Co. v. McClinton, 146 S.W.2d 466 (Tex. Cir. App. 1940). the Texas court held that proof of the contractor's negligence was necessary before the plaintiff could recover for damage caused by removing stumps from the highway right of way in front of his house. Where the contractor is not shown to be negligent, as in Nelson v. McKenzie-Hague Co., 192 Minn. 180, 256 N.W. 96 (1934), he will not be held liable for property damage to a neighboring property owner on a nuisance theory, despite the annoying consequences of his blasting, pile drivers and other noisy machinery, since the state, under its sovereign authority, had delegated the highway construction to the defendant.

Highway Operation

The cases concerning complaints arising out of use of the highway confuse noise and vibration. In many cases, the plaintiff's attorney lumps the noise and vibration together in one allegation. Thus, in Northcutt v. State Road Department, 209 So.2d 710 (Fla. App. 1968), the court restated the plaintiff's claim thus,

> "Briefly, their complaint alleged, inter alia, that they had purchased and constructed a house and improvements on real property located in North Miami, Florida, for the approximate amount of $40,000. The individuals and the real property were in good physical condition until the defendent, State Road Department, began and completed the construction, maintenance and operation of the North-South Expressway, a limited access, federally financed interstate highway known as State Road 9-A. They claim that the defendant placed the limited access right-of-way to the interstate highway very close to their real property. They alleged that the constant use of the quiet residential side street as an access road to the highway by earth moving equipment, dump trucks, concrete mixers, cranes, bulldozers, machinery, etc., during and after the construction of the interstate highway was a direct, and proximate cause of certain damages to their house and

> real property; thus causing the house to become structurally unsound and uninhabitable, and that their damage was irreparable and continuing. They alleged that the defendant had constructed, maintained and operated the interstate highway so as to cause heavy industrial and commercial traffic to use it so near to their property as to cause excessive shock waves, vibrations, and noises, at all hours of the day and night which impaired their health and caused them to lose sleep, become ill and nervous and deprived them of the use and aesthetic beauty of their property, causing it to lose its value for residential purposes so that it cannot be sold or finan-ed for any use or purpose. They maintain that the defendant did not condemn sufficient property to provide for the proper construction, maintenance and operation of the interstate highway system, and the access roads, or their safe operation, and that they had been deprived of the beneficial use and enjoyment of their property and that this amounted to a taking of their private property without just compensation and without due process of law. They prayed that the court order the State Road Department to institute eminent domain proceedings against their property so that they could recover just and full compensation, as determined by a jury, together with interest, cost and attorneys' fees.

Highway operation complaints differ primarily from highway construction cases in that the latter are temporary annoyances while persistent and excessive vibration from a highway in use becomes a permanent nuisance.

Inadequacy of Nuisance Law

Although the language of the complaints is often couched in terms of nuisance law, it has proved to be an unsatisfactory tool in dealing with offensive highway vibration. Courts treat as a nuisance anything that works harm to an individual or the public. A public nuisance affects the public at large, while a private nuisance affects an individual or a small group only. Private parties are not allowed to bring public nuisance actions, which are usually filed by the District Attorney or the Attorney General, unless they can show that they have suffered "special damages," distinct and different from the kind suffered by the public as a whole. While nuisance suits are effective in some vibration cases brought against private defendants, they are inappropriate in highway vibration cases because of the "legalized nuisance doctrine." This recurring doctrine is based on the rationale that highway nuisances such as noise, air pollutants, and vibration are incidental to the needs of a functioning technological society, the price of progress, and that the environmental costs are expected to be borne by the public. Courts have consistently held that the plaintiff who lives on a public street, no matter how offended he may be by the legislatively authorized highway placed adjacent to his property, must put up with the consequential effects. See Campbell v. Arkansas State Highway Commission, 183 Ark. 780, 38 S.W.2d 733 (1931). It's a nuisance, but it's a legalized nuisance.

Courts further argue that to internalize the economic impacts suffered by neighboring homeowners would be so financially prohibitive that it would effectively halt road construction. See Thomsen v. State, 284 Minn. 468, 170 N.W.2d 575 (1969). Further, as the court stated in Deaconess Hospital v. Washington State Highway Commission, 66 Wash.2d 378, 403 P.2d 54 (1965), "Nothing which is done or maintained under the express authority of a statute, can be deemed a nuisance." Thus, no matter how much a highway may be a nuisance in fact, it cannot be a nuisance in law and the legal remedies of private and public nuisance, so useful in correcting other environmental insults, cannot be used against highways authorized by law. Nevertheless, much of the language used in nuisance cases is carried over into the eminent domain and inverse condemnation cases concerned with noise and vibration. For instance, in Cheek v. Floyd County, 308 F. Supp. 777 (N.D. Ga. 1970), the Court spoke in nuisance terms, stating that a plaintiff could recover damages for traffic vibrations if he could show that the injury suffered by him was distinguishable from that suffered by the public in general, and that the vibrations and noise were so severe as to rise to the level of a "legal nuisance" (legislative authorization of the complained highway) which usually serves as an effective defense for the state in such suits.

Private Party Defendants

In suing to abate annoying highway vibration and noise, plaintiffs sometimes sue private parties whose almost exclusive use of a particular stretch of road makes them an easy target. In Coon v. Utah Construction Co., 228 P.2d 997 (1951), the plaintiff sought to recover damages to his home allegedly caused by the defendant's heavy trucks in their passage to and from its place of business. The court denied recovery, concluding that the operations of the defendant's trucks on a public highway was a lawful use which did not create a nuisance nor any legally compensable damage. Similarly, in Bassham v. Shreveport Transit Company, 227 So.2d 160 (La. App. 1969), the court denied recovery to a plaintiff whose home's cracked walls were allegedly caused by excessive vibrations from the transit company's vehicles. The defendant's lawful use of the road was held to be reasonable and no ground for liability.

Inverse Condemnation

Inverse Condemnation is the legal tool which has evolved to give the damaged property owner relief from the consequential effects of a government project. It is to be contrasted with direct condemnation proceedings expropriating land for the project brought by the government before work begins. In an inverse condemnation proceeding, the injured property owner proceeds against the government for damages which have been caused by a state undertaking such as construction or operation of a highway and which have not been compensated for in the original condemnation proceeding. Such claims, while often evident at the time of the original condemnation proceeding, are not paid then because of their speculative nature.

Severance Damages

Courts, in inverse condemnation suits, frequently treat plaintiffs whose property is partially taken for a highway differently from property owners whose land is adjacent to the highway but not taken. This is true even in states with a "damaging" clause. Such courts analogize the award for vibration effects to severance damages in an eminent domain suit. Severance damages, which are awarded when part of a tract is physically appropriated, are measured by the depreciation in the fair market value of the remaining area. They reflect the decline in value of the property not taken caused by the expropriation. Spies and McCoid, "Recovery of Consequential Damages in Eminent Domain," 48 Va. L. Rev. 437, 441 (1962). If the complainant's property has been taken for the highway, as in Mississippi State Highway Commission v. Colonial Inn, Inc., 246 Miss. 422, 149 SO.2d 851 (1963), where an easement twenty feet in length and 5 feet in width, approximately .02 of an acre, was condemned recovery will follow. In the Colonial Inn case, a judgment of $9,210 was upheld to compensate for the diminution of value including, but not limited to, increased noise and vibration.

In Thomsen v. State, 170 N.W.2d 575 (1969) a property owner whose land was not taken by a new four lane truck highway, the travelled portion of which was within ten feet of the plaintiff's home, brought suit to compel an award, claiming the highway department had intentionally narrowed the right of way so as to avoid a taking and payment of compensation. The Minnesota Constitution states that, "Private property shall not be taken, destroyed or damaged for public use without just compensation therefor, first paid or secured.", Minn. Const. Art. 1, #13. The court's explanation of why recovery for damages caused by the increased noise and vibration should be denied unless the plaintiff could, on remedy sho evidence of "special damages," illustrates the outcome determinative issues in such suits,

> "It is clear, however, that not every conceivable kind of injury to the value of adjoining property resulting from highway construction is "damage" in the constitutional sense. Wolfram v. State, 246 Minn. 264, 74 N.W.2d 510; McCarthy v. City of Minneapolis, 203 Minn. 427, 281 N.W. 759. Thus, while a reduction in property values may result from the noise, light, vibration, or fumes produced by the proximity of increased vehicular traffic on a newly constructed highway, such consequential damage is not usually treated as "damage" in the constitutional sense. State ex rel. State Highway Comm. v. Turk (Mo.) 366 S.W. 2d 420; State By and Through Road Commission v. Williams, 22 Utah2d 331, 452 P.2d 881. See, Wolfram v. State, supra; McCarthy v. City of Minneapolis, supra. Noise, light, vibration, and fumes from traffic on modern four-lane highways are "inconveniences that are reasonably incident to the prosecution of necessary public enterprises, "and as such must be and are borne by the public at large. Stuhl v. Great Northern Ry. Co., 136 Minn. 158, 163, 161 N.W. 501, 503. The cost

of compensating all owners of property adjacent or proximate to newly constructed highways affected by these side effects would be so prohibitive that it would effectively halt the construction of highways by the state. See Northcutt v. State Road Dept. (Fla. App.) 209 So.2d supra. Therefore, it has been held that in order for an omitted property owner to force a condemnation and thereby recover for such consequential damage to his property, the damage must be direct, substantial, and peculiar to him, in that it differs markedly from the damage suffered by the public at large as a result of the construction of the highway. See City of Crookston v. Erickson, 244 Minn. 321, 69 N.W.2d 909."

In People, Department of Public Works v. Volunteers of America, 98 Cal. Rptr. 423 (Cal. App. 1972) the court awarded damages for highway noise and vibration even though the highway was not built on land taken from the plaintiff. However, some of his land was taken and used for a freeway buffer zone bringing him within the ambit of that class of property owner whose land has actually been dondemned and to whom severance damages, including damages for annoying noise and vibration, are awarded.

In Dennison v. State, 22 N.Y.2d 408, 293 N.Y.S.2d 68 (1968) the court approved an award to the owners of a colonial frame house situated on a large wooded lot through which a new highway was constructed. In assessing damages, the loss of privacy and seclusion, the loss of view, the traffic noise, lights and odors were all lumped together as factors causing consequential damage to the remaining property, to be assessed as part of the severance damages due the plaintiffs.

Special Damages: The Outer Limits of Recovery

As noted in Thomsen v. State, supra, even when there has been no taking of property or physical damage, in the appropriate case a court will make an award to a property owner who can show that he has suffered by others in the neighborhood. This doctrine offers a loophole to courts seeking to find a means to give a plaintiff an award. In the Thomsen case, supra, which involved a particularly compelling fact situation, the court after reviewing all the legal rules pointing toward dismissal of the home owner's claim, sent the case back to the lower court with instructions to retry the case with particular attention to the existence of special damages. See also Yakima v. Dahlin, 51 Wash. App., 129, 485 P.2d 628 (1971) and Cheek v. Floyd County, 308 F. Supp. 777 (N.D. Ga. 1970).

Special Plaintiffs

Special damages appear more likely to be found in the case of certain types of plaintiffs, such as schools, hospitals, and churches, which receive better treatment from the courts. The qualities of quiet, tranquility, and privacy have been held by the courts to be requirements of such institution, and noise and vibration effect a different type of damage on them from that offered by the public generally.

In Fleetwood Synagogue, Inc. v. State, 60 Misc.2d 326, 302 N.Y.S.2d 898 (Ct. Claims 1970) the state appropriated a strip of land approximately one hundred feet long and ten feet deep and took an easement over an adjacent strip. The court awarded $37,150 for damages primarily based on increased noise.

In Board of Education v. Palmer, supra, the court held that, even though no land had been appropriated for the highway, the environmental effects of the road were so overwhelming as to effectively destroy the beneficial use of the property as a school. The court allowed the inverse condemnation proceeding even though New Jersey is a "taking" jurisdiction. See also New Jersey v. Board of Education, 3 E.R.C. 1159 (197); State v. Board of Education, 116 N.J. Super. 305, 282 A.2d 71 (1971).

However, see, in contrast, United States v. Certain Parcels of Land, 252 F. Supp. 319 (W.D. Mich. 1966) in which it was held that the noise, dust and vibration from the highway complained of by the school board was, on the evidence presented, not substantial enough to justify an award. See also Hollywood Baptist Church v. State Highway Department, supra.

Procedure

Professor David Mandelker believes that inverse condemnation law is so procedurally technical and varies so from state to state that no easy generalizations can be made as to the procedures for bringing suit and as to the limits of liability. Mandelker explores in the report, "Inverse Condemnation: The Constitutional Limits of Public Responsibility," prepared under Contract No. CPR 11-8682 between the U. S. Department of Commerce, Bureau of Public Roads and the Washington University School of Law in 1964. While the report is mainly concerned with cases arising out of damage claims from floods or landslides, the same legal principles govern in vibration cases in deciding whether the court should award consequential (unexpected or indirect) damages. Mandelker concludes that the limits of liability have never been satisfactorily worked out in the eminent domain/inverse condemnation field.

Indeed, a survey of the cases in the noise and vibration area reveals that courts within the same state may take different positions on the same issue. His report is addressed to procedural and pleading matters and includes appendices analyzing each state's laws as to hos such claims are brought. His general conclusions as to how inverse condemnation suits, including claims arising from vibration are brought states.

> "The development of inverse condemnation procedures has been left to the vagaries of judicial development in 50 jurisdictions. The result is a complex body of doctrine difficult to survey except in the most incremental fashion. (For a detailed survey of state inverse procedure see Appendix A). A first glance at the constitutional basis of inverse law is an invitation to mistaken expectations. Constitutional provisions in all states either explicitly guarantee or have been construed to guarantee that compensation will be paid for property taken for public use.[220] However, only twenty of fifty states take the simplest and most direct route and permit the aggrieved landowner to file a common law action for inverse

damages.[221] The rest employ a variety of more or less complicated procedures: a special statutory procedure,[222] a writ of mandamus to compel the institution of condemnation proceedings,[223] or a qualified injunction to restrain the public agency pending the institution of proceedings to pay compensation.[224] Several states have not yet been presented with the question.[225] The available procedures will briefly be reviewed in turn.

The most direct path into court is an action at law in which the petitioner pleads his damage and the constitutional guarantee of compensation. However, the action at law is procedurally less advantageous to the petitioner than a state-initiated condemnation proceeding. When the state initiates the proceeding the procedural position shifts, and some evidence points to more liberal attitudes toward recovery in this context than in the inverse action.[226] Furthermore, the inverse plaintiff must stand the costs if he loses, and California is one state that defines costs to include a reasonable attorney's fee.[227] Whether inverse claimants are deterred by this potential financial burden is certainly open to question.

A second method of obtaining inverse relief is the suit in mandamus to force the commencement of condemnation proceedings by the highway authority. Apparently a simple and direct remedy based upon the statutory or constitutional duty to pay compensation, the origins of mandamus as a prerogative writ have led to procedural difficulties which inhibit its usefulness, even in the presence of a clear duty to compensate. Technically, mandamus is only a first step to the condemnation proceeding, and all questions about compensation should in theory be decided in the condemnation action. But the two actions have not been so clearly separated, tension has developed over the functions to be assigned to each, and the scope of mandamus has varied considerably. In one state, decisions about substantive issues are largely left to the mandamus action, while in another they are relegated to the mandated condemnation proceeding. Furthermore, the mandamus proceeding may be dismissed if preliminary questions of compensability cast doubt on the right to have a condemnation proceeding at all. This issue is tied up, in turn, with the basis of the mandamus action, which may rest alternatively on a statutory or on a constitutional command.

A third procedure is relief by qualified injunction. In this proceeding, the petitioner requests a restraining order against further construction or entry on his land unless compensation is paid for damage done. A qualified injunction is most useful to the landowner whose property is damaged at the time of construction. Unless a court is willing to enjoin the use of a completed facility, the qualified injunction also issues as the first step toward a compensation proceeding, the question of compensation will usually be tried in the injunction suit.

A fourth possibility is a statutory procedure. The statute parties to start condemnation proceedings, it may authorize an action at law for damage to property, or it may provide for a cause of action at law for damage to property, or it may provide for a cause of action limited to specified substantive items of damage. Venue and limitations requirement may also be included. Since the inverse action has a constitutional basis, the only serious difficulty is that the statute may so burden or qualify the constitutional remedy that it violates the constitutional guarantee of compensation. Excessive burdening could occur because of procedural obstruction which the statute sets to the cause of action, such as an unduly short statute of limitations, a claim-filing requirement, or the taxing of attorneys' fees to a losing plaintiff.[228]

The statutes may authorize a claims procedure rather than direct recourse to a court action. Claims procedures vary considerably in detail, and include legislative determinations, sometimes with administrative or judicial advice, administrative determinations, and proceedings before a special court. When the statute makes the claims procedure the exclusive remedy, the problem of burdening the constitutional cause of action once more arises with the added note that courts are often jealous of surrendering jurisdiction.

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220. See Appendix A.

221. See Appendix A. Arizona, Delaware, Georgia, Idaho, Kansas, Kentucky, Louisiana, Maine, Mississippi, Missouri, Nebraska, North Carolina, North Dakota, Oklahoma, Oregon, South Carolina, South Dakota, Texas, Washington, Wisconsin. A few states make more than one remedy available.

222. Six states, see Appendix A. California, Indiana, Massachusetts, New York, Pennsylvania, Tennessee.

223. Seven states, see Appendix A. Illinois, Iowa, Minnesota, New Jersey, Virginia, West Virginia. Both mandamus and qualified injunction are apparently available in Alabama. Iowa is similar.

224. Seven states, see Appendix A. Alabama, Arkansas, Florida, Iowa, Maryland, Michigan, Utah.

225. Ten states, see Appendix A. Alaska, Connecticut, Hawaii, Montana, Nevada, New Hampshire, Ohio, Rhode Island, Vermont, Wyoming.

226. See the discussion of chances for recovery under the federal eminent domain clause in Note, 50 Yale L.J. 668, 678 (1941).

227. Cal. Gov. Code §§ 947 (Deer. Supp. 1963). This section no longer explicitly authorizes the taxing of an attorney's fee against a losing plaintiff. He is to be taxed for allowable costs," and there is no indication from the legislative history that an attorney's fee is not included.

228. Courts have been concerned with the problem of costs sufficiently heavy to act as a deterrent to the exercise of matters of right. If a state were to burden a remedy with excessive procedural or substantive inhibitions there is considerable evidence that constitutional invalidity would result. See the discussion in People ex rel. O'Meara v. Smith, 374 Ill. 286, 29 N.E.2d 274 (1940).

Conclusion

The courts have had difficulty in handling highway noise and vibration cases. In the words of the Supreme Court of Louisiana, in Reymond v. State Department of Highways, supra, at p. 380, "The courts of this state have floundered from one theory to another to no theory at all---." There has been controversy and a division between the different state courts as to whether a property owner whose land is adjacent to, but not taken by, a highway or even a property owner part of whose land is condemned for the road may recover damages for the noise and vibration. Although the law must be researched for each separate jurisdiction, a number of generalizations can be made. If tangible injury such as cracked walls and broken windows can be shown to have been caused by highway construction or operation, the court will award damages. The plaintiff usually recovers whether his property has been formerly appropriated or is merely adjacent to the highway. If the complainant seeks damage for annoying noise and vibration, the state's constitutional expropriation provisions must be examined. Although recovery is easier in a state which awards compensation for state actions "damaging" the plaintiff's property, it is possible in a state which gives recovery only for a "taking" of property, if it can be shown that the vibration is so severe that it interferes with the plaintiff's use of the property. A further analysis must be made as to whether it is merely adjacent to it. Recovery for annoying vibration has been limited to those whose property has been partially expropriated, as severance damages, while owners of property adjacent to the highway are denied recovery unless they can show special damages different from those suffered by the community at large. The types of plaintiffs who have claimed special damages successfully include hospitals, schools, and churches.

Persistent Sources of Vibration

Vibration cases are not new, and antedate the invention of the automobile; there are scores of cases, beginning in the last century, concerning persistent annoying vibration from electric generation plants, subways, and railroads.

Railroads

Railroad cases are of particular interest since the damages done by the vibrations are so similar. One important distinction is that highway operation for motor vehicular use is more clearly a state activity than operation of a railroad. However, even in the turn of the century railroad cases, plaintiffs ran into the problem of state licensing and regulation of railroads acting to cast a veil of state authority over the nuisance. In Wiener v. Pennsylvania R. Co., 292 Ill. App. 303, 10 N.E.2d 981 (1933) the plaintiff's recovery for vibration damages was barred unless he could show that the railroad was being operated negligently or unlawfully. Applying a similar rationale, the same result was reached in Chicago G.W. Ry. Co. v. First Methodist Episcopal Church, 102 F. 85 (8th Cir. 1900).

Other railroad cases illustrate an earlier application of some of the doctrines discussed above such as the special damages doctrine applied in Louisville R. Co. v. Foster, 108 Ky. 743, 57 S.W. 480 (1900), where the court held that recovery would be allowed only if the plaintiff could show that damage was not fairly incidental to the usual operation of the railroad. Similarly, in Kinsay v. Union Traction Co., 169 Ind. 563, 81 N.E. 922 (1907), the court awarded damages to an adjacent land owner whose home had developed cracks caused by vibration from the defendant's railroad, holding the defendant liable for the tangible special damages proven. The old railway cases, while interesting, are not as forceful authority as that readily available from the large body of adjudicated cases concerning highway vibration. An exception is perhaps the most significant railroad vibration case, Richards v. Washington Terminal Co., 233 U.S. 546, 34 S. Ct. 654 (1914) which is historically important because it opened the door to the awarding of consequential damages to neighboring landowners. While the case is primarily concerned with the terminal's flushing of smoke and gases onto a neighbor's property, with vibration playing a minor part, the Supreme Court's opinion sets forth legal principles which have been applied to determine whether consequential damages should be allowed for injuries arising out of governmental operations. The Court held that while the government's operation of a project ordinarily would legalize what otherwise would be a public nuisance, that recovery would be allowed in cases in which the activity, in effect, worked damages which were direct and peculiar to the plaintiff resulting in a taking of the property. Thus, the Richards case opened the doors of the courts to the special damages doctrine.

It has been suggested that the property owner is more likely to receive compensation for consequential damages where the condemner is a profit making corporation acting as a delegate of the government. When the government itself is involved as the actor, operating military aircraft, etc., it is more likely that a court will be impressed by sovereign immunity arguments than when the damage is done by a construction company.

See Comment, "Eminent Domain Valuations in an Age of Redevelopment: Incidental Losses," 67 Yale L.J. 61, 94 (1957).

Machinery

A number of cases have arisen out of vibration from electric utility plants. Here, the law of nuisance comes into play if the plant spoils the enjoyment of life and full use of property of its neighbor. A series of cases commented on in 4 American Law Reports, Annotated 3d 902, Annotation, "Electric Generating Plant or Transformer Station as Nuisance," The Lawyer's Co-operative Publishing Company, Rochester (1973) bear out the observation that recovery is easier in such cases than in the highway and railroad vibration cases. This is probably because the ambit of possible claimants is much smaller, being confined to dwellings within an easily marked and narrow radius of the plant, while the possible plaintiffs in a highway suit stretch along the entire length of the road.

Aircraft Operation

Noise and vibration from aircraft landing and taking off from a neighboring airport have been held to be such an interference with the owner's property as to amount to a taking. See United States v. Causby, 328 U. S. 256, 66 S. Ct. 1062 (1946) and Griggs v. Alleghany County, 369 U.S. 84, 82 S. Ct. 531 (1962). The recovery in Griggs was against the county which planned and operated the airport, while the recovery in Causby was against the federal government which operated both the offending military flights and airfield. The cases deriving from Griggs and Causby are more concerned with noise than with vibration. Significant vibration problems have arisen out of sonic booms from aircraft operations. However, the courts have treated sonic booms as extraordinary events and have been more reluctant to grant recovery than in the noise and vibration cases arising out of routine commercial aircraft operations.

Recently, litigation has centered around the attempts of communities to regulate airport noise. In City of Burbank v. Lockheed Air Terminal, Inc. 411 U.S.624, 93 S. Ct. 1854 (1973), the United States Supreme Court struck down a municipality's ordinance barring night operation of an airport on the ground that the Noise Control Act of 1972 had preempted the field, barring any state and local initiatives against aircraft noise.

EXTRAORDINARY VIBRATIONS

Sonic Booms

The law concerning recovery for damages by sonic booms has, to date, developed in a restrictive manner. Early sonic boom litigation faltered because of the unavailability of experts to testify that the aircraft shock waves possessed the potential to cause such damage. That sonic booms can cause physical damage to property is now common knowledge, but sonic boom litigation is difficult because the booms are held to be a byproduct of a sanctioned government activity (all of the complaints to date arising out of military activity). Litigation is mired in a welter of confusing theories including actions brought under the Federal Tort Claims Act 28 U.S.C. 2674, as well as conventional common law suits brought under theories of negligence, trespass, nuisance, and unconstitutional taking. While a number of cases in the last few years had suggested that there might be an opening up of liability (see, e.g., U.S. v. Gravelle, 407 F.2d 964 10th Cir. 1969), the United States Supreme Court's decision in Laird v. Nelms, 406 U.S. 797, 92 S. Ct. 1899 (1972) seriously restricted recovery on what had been thought the best vehicle for relief, the Federal Tort Claims Act. In Laird, the Court held that the plaintiff could not recover without a showing of negligence either in the planning of operation of the flight. The Court stated that the Act did not authorize a suit against the government based on strict liability for conduct of an ultra-hazardous activity.

The status of sonic boom litigation is up in the air after the Laird decision and a number of legal writers have commented on possible directions future litigation might take. See, e.g., Note, "Utility, Fairness and the Takings Clause: Three Perspectives on Laird v. Nelms," 59 University of Virginia Law Review 1034 (1973); Note, "Torts--Federal Tort Claims Act--Government Immunity from Strict Liability for Damages Caused by Sonic Boom" 47 Tulane Law Review 920 (1973).

Whatever future direction sonic boom litigation may take, its impact on highway vibration cases probably will be small because of the difference in degree between the two phenomena. Sonic boom cases are more akin to blasting cases, where the harm is done through one sharp explosion rather than through the steady vibration from highways.

Environmental Law Suits

The wave of environmental litigation which began in 1970 has not yet effected vibration cases. The Noise Control Act of 1972, 42 U.S.C. #4901-18 (Supp. 1973) which is addressed to audible sound and not to vibration has not yet been interpreted by the courts. Significantly, however, a number of environmental groups have tried to halt highway projects because their noise effects had not been fully disclosed in the environmental impact statement which the agency is required to file, pursuant to the National Environmental Policy Act (NEPA), 42 U.S.C. #4321 et seq., before beginning work on the project. The plaintiffs in these cases averred that the impact statement filed was skimpy or procedurally inadequate. Under NEPA, if there is no adequate impact statement making a detailed statement on the expected environmental effects, including noise, an injunction may be entered, halting the project. The plaintiff was successful in the I-291 Why? Assn. v. Burns, 6 E.R.C. 1275 (U.S.D.C. Conn. 1974) in having such an injunction issued. See also M.A.D. v. Volpe, 5 E.R.C. 1625 (U.S.D.C. Myd. 1973); Scherr v. Volpe, 466 F.2d 1027 (7th Cir. 1972); Conservation Society of Southern Vermont, Inc. v. Volpe, 343 F. Supp. 761 (U.S.D.C. Vt. 1972); Julius v. Volpe, 349 F. Supp. 88 (U.S.D.C. Iowa 1972) for additional cases in which environmentalists tried to stop highway construction on the ground that noise impact had not been adequately assessed. None of these cases mention vibration. They are noise cases, but they are significant: (1) because the courts consistently, in the past, have confused noise and vibration, and (2) because they are recent decisions in a new and undeveloped area of the law. Federal courts have interpreted NEPA in more than 400 lawsuits. Although no NEPA case has ever been decided on the basis of highway vibration, it is the sort of adverse environmental effect which must be assessed under the statute. Environmental litigation is an area in which new developments in highway vibration law may be expected to develop.

Conclusion

Although there are many cases concerning damage from such various sources as highways, railroads, industrial plants, blasting operations and airplanes, which offer helpful analogies, it appears that the best authority for future highway vibration litigation is the considerable body of adjudicated highway cases. Most of these have been brought as inverse condemnation suits and are governed by the technical substantive rules of eminent domain law. The loophole by which the courts have expanded liability for annoying, but not physically damaging, vibration has been the special damages rule whereby the plaintiff must show that his injuries differ in degree and kind from the community at large. Whether this will be expanded in the future by environmental litigation remains to be seen. As courts define unacceptable standards under the Noise Control Act of 1972, and the National Environmental Policy Act, special damages may be more loosely defined to include environmentally annoyin vibration which effects the community at large. But at the present time, recovery is governed by the strict rules outlined herein.

LAW RELATED LITERATURE CONCERNING HIGHWAY VIBRATION

Beranek, "Street and Air Traffic Noise--And What We Can Do About It," UNESCO Courier, July 1967 at 12, 14.

Brazener, Robert, "Traffic Noise and Vibration From Highway As Element of Damages and Eminent Domain,. 51 American Law Reports Annotated 3rd 860, Lawyers Cooperative Publishing Company, Rochester, New York (1973). This excellent annotation in the ALR series is an analysis of recent cases seeking compensation for property damage caused by highway noise and vibration.

Case Comments, "Eminent Domain: Inverse Condemnation--What Constitutes a Taking," 21 University of Florida Law Review 257 (1968). This short comment analyzes state law on property damaged by adverse consequential effects of highways.

Gray, Oscar S., "Environmental Requirements of Highway and Historic Preservation Legislation," 20 Catholic University Law Review 45 (1970). This article by a Department of Transportation official explains the general duty of the Department under the National Environmental Policy Act and the Highway Act to avoid adverse environmental effects from highway design, construction, and operation.

Highway Research Board, Severance Damages--Noise, Inconvenience, etc., Highway Research Circular, National Academy of Science, Washington, D.C. (1971). This report contains a summary of court decisions discussing severance damages to the property owner.

Hildebrand, James L., "Noise Pollution: An Introduction to the Problem and an Outline for Future Legal Research," 70 Columbia Law Review 652, 662 (1970). This article discusses the technical background and need for noise control legislation, including infrasound and ultrasound. Some of the proposals advanced include mass transit and construction of quieter road surfaces. Traffic noise is discussed at page 672 to page 679 and aircraft noise from page 679 to page 682.

Mandelker, Daniel, Inverse Condemnation: The Constitutional Limits of Public Responsibility, Bureau of Public Roads, Washington, D. C. (1964). This report, prepared under a contract from the Bureau of Public Roads and the Washington University School of Law at St. Louis, concerns inverse condemnation suits action brought by land owners who have been damaged by highway activity such as noise, vibration, erosion of lateral support, etc. While Mandelker does not focus on vibration cases, the legal principles analyzed are those which are applicable in common law vibration cases in inverse condemnation lawsuits.

Oklahoma University Research Institute, Valuation and Compensability of Noise, Pollution, and Other Environmental Factors, Highway Research Board, National Academy of Science, Washington, D. C. (1971). This report analyzes cases arising from highway oriented pollution in urban areas.

Organization for Economic Cooperation and Development, Urban Traffic Noise: Strategy for an Improved Environment, Paris, 1971. This volume is a report of the consultative group of transportation research of the Organization for Economic Cooperation and Development, which surveys current administrative and legislative practices in Canada, France, Italy, Japan, Netherlands, Scandinavia, Switzerland, and the United Kingdom. While the foc-s is on noise and not vibration, it serves as a background on the European regulatory framework.

Sackman, J. L., "Proximity Damages," Appraisal Journal, April 1969, pages 177-199. This article summarizes the approaches used by appraisers in calculating monetary awards for abutting property owners who will be affected by the adverse consequences of highway operation.

Zoellner, George L., Selected Problems Relating to Highway Laws, 1962, Highway Research Board Special Report 76, National Academy of Sciences--National Research Council, Washington, D. C. (1962). This short paper was an address delivered by the Deputy Chief Highway Counsel and Assistant Attorney General of Colorado concerning eminent domain and inverse condemnation problems experienced by highway departments. It reviews

the major traditional conservative sources of authority denying recovery to damaged property owners prevalent in the older cases.

LAW RELATED LITERATURE CONCERNING ENVIRONMENTAL VIBRATION

General

American Jurisprudence Proof of Facts Annotated, Volume 8, Nuisance, at pages 527, 531, 540-542; Volume 18, Airport Noise, page 123; Volume 26, Community Noise, page 101; Lawyers Cooperative Publishing Company, Rochester, New York (1960). This legal encyclopedia offers the trial attorney suggested questions and answers in handling witnesses in a noise/vibration case.

Annotation, "Electric Generating Plant or Transformer Station as Nuisance," 4 American Law Reports Annotated 3rd 902, 918, Lawyers Cooperative Publishing Company, Rochester, New York (1965). This ALR annotation discusses nuisance suits brought against power plants because of vibration, noise, air pollution, etc.

Annotation, "Liability for Property Damage Caused by Vibrations or the Like Without Blasting or Explosion," 79 American Law Reports Annotated 2nd 966, Lawyers Cooperative Publishing Company, Rochester, New York (1961). This thorough ALR annotation surveys damage caused by vibration in tort law suits. It should be compared with the eminent domain annotation at 51 ALR 3rd mentioned above. The particular vibration producing agencies or instrumentalities discussed include railroads, heavy machinery, subways, quarrying and drilling operations.

Annotation, "Right of Abutting Owner to Compensation for Railroad in Street under Constitutional Provision Against Damaging Property for Public Use without Compensation." 22 American Law Reports Annotated, 145, 187, The Lawyers Cooperative Publishing Company, Rochester, New York (1923). This annotation focuses on noise and vibration caused by railroads. The cases cited support the proposition that any unusual vibration of a building which causes substantial damage to the property supports a cause of action.

Bigham, D. Alastair, The Law and Administration Relating to Protection of the Environment, Chapter 9, pages 177-186, Oyez Publishing, London (1973). This survey treatise on British environmental law includes a chapter on noise and vibration. It discusses land use planning control in the routing of highways as a significant noise and vibration control.

Bolt, Beranek, and Newman, Inc., Chicago Urban Noise Study, Bolt, Beranek, and Newman, Cambridge, Massachusetts (1970). This report was the background study for the Chicago ordinance which regulates both noise and vibration.

Comment, "The New York City Noise Control Code: Not with a Bang, but with a Whisper," 1 Fordham Urban Law Journal 446 (1973). This comment gives a good description of the New York City Noise Control Code, which, in pertinent part, passes on vibration problems from rapid transit systems, airplanes, and attempts to limit noise in streets adjacent to schools, hospitals and other sensitive areas, and to tunneling permits. It should be noted that the New York City code defines noise in terms of excessive or unusually loud sound and not in terms of vibration. However, the activities sought to be regulated impinge on vibration activities.

Council of State Governments, <u>1974 Suggested State Legislation</u>, Volume 33, Lexington, Kentucky (1974). The proposed model state noise control act set out at pages 10-20 includes vibration by defining noise to include vibration of subaudible frequency. The proposed comprehensive program of noise and vibration control includes control of environmental noise, product noise, labeling requirements, notice to purchasers of real property of the noisiness of the area, setting of ambient standards, adoption of a plan for achieving standards, standards for new construction, workplaces, and airports. The proposed model law suggests establishment of special noise insulation districts. Highways are not specifically mentioned.

Duerden, C., <u>Noise Abatement</u>, Philosophical Library, New York (1971). Chapter 9 of this book about British attempts to control noise pollution deals with legislation and discusses the Noise Abatement Act of 1960 that regulates noise or vibration which is a nuisance. The British Act differs from the American Noise Pollution Act of 1972 in dealing specifically with vibration. However, a review of the British cases dealt with in this survey shows a close similarity in the treatment of noise and vibration by British and American courts. The appendix sets out a series of statutes and ordinances dealing with noise and vibration control.

Kramon, James M., "Noise Control: Traditional Remedies and a Proposal for Federal Action," 7 Harvard Journal of Legislation 533 (1970). This article surveys the legal remedies traditionally available for noise pollution control, which are the same available for vibration control as well. The author concludes that the common law remedies are not effective and proposes a statutory action to regulate noise pollution. The article focuses on changing patterns of government spending in line with the government contract program to require that the recipient pursue technological alternatives which would provide a reasonable degree of quiet.

Lloyd, William H., "Noise as a Nuisance," 82 University of Pennsylvania Law Review 567 (1934). This brief article serves as an introduction to the traditional remedies for recovery in noise nuisance cases. The author points out that noise and vibration are frequently lumped together by plaintiffs since the cases factually present a complex of nuisances in which noise, smoke, vibration, and offensive odors are frequently mingled. In the cases, it is difficult to separate noise from vibration, so recovery and the court's decision are frequently based on the combination of offenses.

McLoughlin, J., The Law Relating to Pollution, Manchester University Press, Manchester (1972). This survey treatise of British environmental law includes a chapter on noise and vibration at pages 77-85 which discusses defenses to noise and vibration lawsuits. The primary emphasis is on noise; however, vibration is treated throughout in conjunction with noise.

Spater, George A., "Noise and the Law:, 63 Michigan Law Review 1373 (1965). In this survey article, which encompasses nuisance cases arising out of both noise and vibration, Spater distinguishes between noise and vibration cases, giving a higher dignity in recovery to the vibration cases. The article is a collection of mostly conservative opinion veering away from plaintiff's recovery. It should be noted that the article predates more recent cases which have allowed recovery to plaintiffs for noise and vibration damage caused by highways.

Blasting

American Jurisprudence, vol. 31, Explosions and Explosives, §37, 38, and 41, The Lawyers Cooperative Publishing Co., Rochester, New York, (1967). This legal encyclopedia gives a short discussion of damage from concussions or vibrations in general and the degree of care required of those carrying on blasting activity. Illustrative cases are footnoted to demonstrate the rules for liability of blasting operators whose vibrations cause damage to adjoining property owners.

Annotation: "Liability for Property Damage by Concussion from Blasting," 28 American Law Reports 2d, 1372, The Lawyers Cooperative Publishing Co., Rochester, New York (1951). This ALR annotation discusses the various legal standards as to what constitutes negligence in the conduct of blasting operations.

Comment, "Blasting in New York: A Reappraisal of the Trespass-Vibration Distinction," 33 Albany Law Review 295 (1969). This student comment reviews the difficulty common law courts have had in dealing with damage caused by vibration from blasting operations.

Decisions, "Torts--Blasting-Liability for Damage from Concussion without Trespass," 28 Brooklyn Law Review 177 (1972). This student note discusses the evolution of New York law on blasting activities and the difficulty of getting an award for vibration damage.

Prosser, William L., Handbook of the Law of Torts, 4th Ed., West Publishing Co., Saint Paul, Minnesota (1971). Blasting activities are discussed in various places throughout the Prosser treatise; however, the most interesting discussion is in section 78 on abnormally dangerous things and activities. Prosser traces the confusion in American law concerning blasting cases which proceed on tort theory, nuisance and other theories.

Recent cases, "Torts--Absolute Liability--Blasting-Concussion Damage," 10 Catholic University of America Law Review 98 (1961). This student note discusses the evolution of blasting and vibration cases in South Carolina and other southeastern states.

Recent cases, "Torts--Blasting--Strict Liability for Concussion Damage," 46 Kentucky Law Journal 636 (1958). This student note discusses the development of blasting/vibration cases in Kentucky which is one of the few jurisdictions continuing to recognize the distinction between damage done by flying debris and damage done by means of vibration, (requiring a higher degree of proof as to the latter).

Health and Job Safety

Lehmann, Phyllsi, "Vibration," Job Safety and Health, January 1974, pages 5-10, U. S. Department of Labor, Occupational Safety and Health Administration, U. S. Government Printing Office Washington, D. C. (1974). In this short article, Ms. Lehmann comments on the adverse health effects which result from excess vibration. She points out that most of the research done on health effects of vibration in the workplace has been done in Europe, where the International Standards Organization has drafted a general guide designed to apply to vibration exposure. Regulatory standards have been promulgated as law in the Soviet Union. Ms. Lehmann's article points to future OSHA activity in the vibration regulation field.

Williams, Charles R., "Soviet Tentative Standards and Regulations for Restricting Noise in Industry," Noise Control, September 1959, pages 44 ff. This article includes a translation of proposed Soviet regulations for restricting noise in industry which also govern vibration. The regulations include guidelines for the design and operation of machinery, plant units, and industrial sites.

Sonic Boom

Caplan, Harold, Some Legal Problems Arising from Supersonic Flight or Boom Time for Lawyers, American Bar Association Section of Insurance Negligence and Compensation Law, Proceedings 1970, page 451, Chicago (1970). A survey of British approaches to the problem of vibration damage caused by supersonic flights.

Comment, "The SST: Lowering the Sonic Boom on Property Owners," 37 Albany Law Review 524 (1973). This student comment focuses on the aggrieved property owner's remedies against sonic boom vibration damage. After surveying insurance, administrative remedies, and various legal theories based on negligence, nuisance, inverse condemnation, and strict liability, the author concludes that the problem of sonic boom vibration damage presents problems difficult to redress.

Comment, "Torts--Federal Tort Claims Act--Sonic Boom--Cause of Action Based on Absolute Liability not Actional be under the Federal Tort Claims Act," 48 Notre Dame Lawyer 727 (1973). This comment discusses the Supreme Court's most recent decision making recovery by property owners damaged by military sonic boom vibration more difficult.

FitzGerald, Gerald F., "Aircraft Noise in the Vicinity of Aerodromes and Sonic Boom," 21 University of Toronto Law Journal 226 (1971). This article surveys the laws of various western European and North American countries concerning the sonic boom problem.

Gray, Oscar S., Environmental Law: Cases and Materials, 2nd ed., Bureau of National Affairs, Washington, D. C. (1973). Professor Gray's case book devotes approximately 90 pages to noise and vibration cases, under the rubric of noise. No distinction is made between noise and vibration in this gathering of cases, most of which are concerned with airplane and sonic boom problems. The examination of legislative materials is confined to the Noise Pollution and Abatement Act of 1970 and the Noise Control Act of 1972.

Hildebrand, J., ed., Noise Pollution and the Law, William S. Hein & Co., Inc., Buffalo, N. Y. (1970). This volume reprints a number of excellent articles on the legal problems caused by sonic booms including (1) Baxter, William F., the SST: From Watts to Harlem in Two Hours, 21 Stanford Law Review 1 (1968); (2) Sonic Booms: Tort Liability, a comment from the Winter 1970 issue of the Journal of Air Law and Commerce, volume 36, pages 117-135; and (3) Sonic Booms: Ground Damage and Theories of Recovery, published in the Autumn 1966 issue of the Journal of Air Law and Commerce, Volume 32, pages 597-606.

Montgomery, John R., "The Age of the Supersonic Jet Transport: Its Environmental and Legal Impact, 36 Journal of Air Law and Commerce 577 (1970). This article focuses on technical problems connected with the SST and sonic booms. It briefly mentions the American sonic boom cases, and concludes by discussing possible future international conventions.

Note, "Torts, The Federal Tort Claims Act--Absolute Liability, the Discretionar. Function Exception, Sonic Booms, Laird v. Nelms," 6 Akron Law Review 105 (1972). This short comment discusses the implications of the Supreme Court's decision in the Laird v. Nelms case which restricted recovery by property owners under the Federal Tort Claims Act.

Note, "Torts--The Discretionary Function, Exception and Absolute Liability in an Action for Recovery for Sonic Boom Damage Brought under the Federal Tort Claims Act for damage caused by sonic booms from military aircraft.

Note, "Utility, Fairness and the Takings Clause: Three Perspectives on Laird v. Nelms," 59 University of Virginia Law Review 1034 (1973). This philosophically searching inquiry conjectures as to future directions in sonic boom litigation following the Supreme Court's restrictive ruling in Laird v. Nelms.

Shurcliff, William A., SST and Sonic Boom Handbook, Ballentine/Friends of the Earth Book, New York (1970). This short paperback volume focuses on the SST controversy of 1970. Approximately half of it is devoted to sonic boom complaints. There is a seven page bibliography at the end.

Taylor, J. P. and Taylor, E. R. G., A Brief Legal History of the Sonic Boom in America, Advisory Group for Aerospace R&D, Paris, France (1969) (National Aeronautics & Space Administration; N70-13139. This report focuses on administrative approaches to the sonic boom problem.

Varner, Robert E., "Legal Aspects of the Sonic Boom," 23 Alabama Lawyer 342 (1962). This short article is an early attempt to deal with the legal aspects of sonic booms. It attempts to compare sonic boom complaints to blasting cases and other types of ultra hazardous activities.

LAW RELATED LITERATURE CONCERNING NOISE CONTROL THAT AFFECT VIBRATION CONTROL

Very little attention has been paid to the environmental effects of vibration in legal literature. However, recent years have seen an explosive increase in the number of articles and books dealing with noise control. Often the legal principles underlying a noise control action and a vibration control suit are similar, if not identical. Therefore, an abbreviated list of law related publications dealing with noise control is included.

American Association of University Women, A Resource Guide on Pollution Control, Chapter B, pages B 1-4, Washington, D. C. (1970). This resource volume on materials concerning pollution contains a short bibliography on legal control of noise and a list of citizen's groups, trade groups and governmental groups interested in noise and vibration control. Some of the sources listed are specifically concerned with transportation and with vibration problems.

The Association of the Bar of the City of New York, "Selected Materials on the Problems of Noise Pollution and Control," 27 The Record 118 (1972). The New York Bar Association's journal reprints a 15 page bibliography of articles on the technical and legal aspects of noise pollution control. Several of the titles refer to vibration, but no distinction is made in the classification system.

Bragdon, Clifford R., "Municipal Noise Ordinances," Sound and Vibration, December 1973, pages 16-22.

Bureau of National Affairs, Noise Regulation Reporter, Washington, D.C. (1971). This two volume weekly service reports developments in the noise control field.

Bureau of National Affairs, Occupational Safety and Health Reporter, Washington, D. C. (1973). This multi-volume weekly service reports developments related to OSHA, an act interpreted by the Department of Labor to cover environmental vibration.

Cohem, Joseph L. and Sharon, Leonard, "Noise and the Law: A Survey," 11 Duquesne Law Review 133 (1973): A good survey which, however, confuses noise and vibration cases. The article treats both private and

public legal remedies giving a good background discussion on private nuisance and public nuisance and the injunctive remedies available to halt such nuisances.

Comment, "Automobile Noise--An Effective Method for Control," 4 University of Richmond Law Review 314 (1970): This short case note is confined to discussion of sounds from automobile engines and exhaust, and does not refer to other sources of automotive noise such as tires, roadways, etc.

Comment, "Noise Abatement at the Municipal Level," 7 University of San Francisco Law Review 478 (1973). This student comment discusses the problems with noise control in California where state and local authority conflicts. The article focuses on both vehicular and air transportation noise problems. While not directly on the point of vibration, it illustrates the approach of legal planners in drafting local noise control laws.

Environmental Protection Agency, Legal Compilation, Statutes and Legislative History, Executive Orders, Regulations, Guidelines and Reports, Noise, Volume 1, Chapter 4, Laws and Regulatory Schemes for Noise Abatement, U. S. Government Printing Office (1973). This survey chapter discusses current federal laws and regulatory schemes regulating noise. Military standards for noise reduction as well as the efforts of other government agencies in the transportation (aircraft and highway) and construction areas to regulate and control noise are discussed.

Environmental Protection Agency, Legal Compilation, Statutes and Legislative History, Executive Orders, Regulations, Guidelines and Reports, Supplement 1, Volume 5, Noise, U. S. Government Printing Office Washington, D. C. (1973). This volume in EPA's legal compilation series contains the text of the Noise Control Act of 1972 together with documents making up the legislative history of federal noise control and abatement laws. It is a necessary background for establishing the parameters of the federal control scheme which focuses on sound and not vibration.

George Washington University, Law and Regulatory Schemes for Noise Abatement, U. S. Environmental Protection Agency Office of Noise Abatement, Washington, D. C. (1971), NTID 300.4. This major report prepared by George Washington University's Program of Policy Studies in Science and Technology served as the background legal study for E. P. A. on its noise abatement authority. While not dealing directly with vibration, it touches peripherally on vibration problems of transportation.

Hatfield, Mark, "Compilation of State and Local Ordinances on Noise Control," Congressional Record, House of Representatives, Volume 115, No. 176 (daily edition), 29 October 1969, pages E 9031 to E 9112.

Hildebrand, James L., editor, Noise Pollution and the Law, William S. Hein and Co., Inc., Buffalo (1970). This 1970 anthology reprints without change a series of articles dating mostly from the early 1960s. Several classic articles on common law noise control are reprinted but most attention is given to sonic boom and airport noise problems.

Note, Statute: "A Model Ordinance to Control Urban Noise Through Zoning Performance Standards," 8 Harvard Journal of Legislation 608 (1971). While this article focuses on noise pollution control, the same analysis and statutory approach would be used in the vibration control field.

Note, "The Noise Control Act of 1972--Congress Acts to Fill the Gap in Environmental Legislation," 58 Minnesota Law Review 273 (1973). This student note, the best single short introduction to the Noise Control Act of 1972, gives a description of the legal remedies at private law available prior to the statute, and discusses the approaches expected to be used under the 1972 law. In passing, the article discusses the Secretary of Transportation's duty under the Federal Highway Act to promulgate noise standards for highways which are compatible with surrounding land uses.

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APPENDIX IV

HUMAN RESPONSE TO BUILDING VIBRATION

The purpose of this review is to survey the literature relevant to human response to building vibration as a part of the overall study of the impact of vibrations related to highway use. The known literature related to human response to vibration is extensive (some have estimated 4,000 relevant reports) and growing at the rate of 75 to 100 papers per year. No attempt was made to present an exhaustive survey. Excellent summaries are available (Griffin, 1973; and Guignard and Guignard, undated; among others). Most of the studies were directed toward vibration experienced by occupants of land, sea, and air vehicles. Many involve the criteria of reduced proficiency and threat to health while the problem to which this study is addressed is that of reduced comfort or thresholds of vibration perception.

Almost without exception published studies have concentrated on the response of humans to vibration as a function of the frequency, magnitude, duration, and direction of application of the vibration stimulus. Virtually nothing has been reported concerning the ways in which environmental, psychological, and socioeconomic factors may influence vibration tolerance.

Terminology

Vibration, with respect to direction, may occur in three translational and three rotational directions. Given the nature of buildings, for the present purpose it is necessary to consider only translational vibration, and that in only two directions. Motion in the foot-to-head direction is generally referred to in this country as <u>vertical vibration</u>. In biodynamics, with respect to a coordinate system of the human skeleton in a normal anatomical position, vertical vibration is designated $\pm a_z$. The 1974 ISO Standards refer to vertical vibration as longitudinal. The term <u>vertical vibration</u> will be used to refer to $\pm a_z$ motion in this review. Similarly, the other two translational motions are $\pm a_x$ (chest to back) and $\pm a_y$ (lateral motion). When referenced to building vibration these two lose some precision so that any motion of wall perpendicular to that of vertical floor vibration is referred to as <u>lateral vibration</u>.

<u>Criteria</u> is a generic term used to indicate some level of human susceptibility to vibration, generally with specific reference to comfort, performance or health.

Existing Criteria

The earliest reported study directly related to building vibration was authorized in England by the Board of Trade in 1902. The study was initiated in response to complaints by Hyde Part residents of building vibrations induced by traffic on the Central London Railway. The basic conclusions, reported by Mallock (1902), were that vibrations of approximately 0.01 g were noticeable and those between 0.04 g and 0.05 g were considered unpleasant.

Mellville (1903) was among the first to note that human response to vibration was frequency dependent, probably the most single agreed upon aspect of human vibration susceptibility by current investigators. Melville (1903) concluded that susceptibility was a constant function

force x frequency = mass x rate of change of acceleration.

The unit for rate of change of acceleration is called the "jerk."

Digby and Sankey (1911) reported that susceptibility to vibration was a function of velocity. Values of 0.100 to 0.125 in/s were established as faintly perceptible.

Probably the most cited study, even today, was conducted in Germany by Reiher and Meister (1931). They concluded that vertical vibration was felt more strongly than horizontal vibration. They further concluded that for small amplitudes vibration susceptibility was a function of maximum velocity; while for larger amplitudes it was a function of acceleration. This response data is based upon laboratory subjective response tests conducted with ten (10) male subjects between the ages of 27 to 37.

Zeller (1933) concluded that susceptibility to vibration could be quantified as a function of rate of change of acceleration by the following equation:

$$E = 16\pi^4 X^4 f^3$$

where X = displacement in inches
f = frequency in Hz

Zeller (1933) further proposed the Pal as the unit of subjective intensity

where $\text{Pal} = 10 \cdot \log_{10}(E/E_o)$

where E is the measured vibration
E_o is the reference value of 0.5

Pal values associated with given criteria levels were listed as

Pal	Criterion Level
0 - 10	Threshold of perception
10 - 20	Generally perceptible
20 - 30	Traffic vibration unbearable by human beings in buildings
30 - 40	Vibrations in smoothly running vehicles, slight damage to buildings

On the basis of his investigation, Zeller (1933) concluded there was little difference in susceptibility with respect to direction of vibration.

Jacklin and Liddell (1933) used only three levels in their study - perceptible, disturbing, and uncomfortable. From this work conducted at Purdue University, these investigations developed the following quantification of intensity

$$K = Ae^{0.6f}$$

where K = A constant, called the Comfort Index

A = Maximum acceleration in ft/sec^2

e = Base of the natural logarithm

f = Frequency in Hz

The K values associated with uncomfortable and disturbing vertical vibration were

Uncomfortable	64.7
Disturbing	31.2

Coermann (1940), using the results of Reiher and Meister and following the convention of Zeller (1933), proposed the following criteria.

$$J = 10 \cdot \log(V_1/V_o) \text{ for amplitudes of less than .02 mm}$$

$$J = 5.4 \cdot \log(a_1/A_o) \text{ for amplitudes of greater than .02 mm}$$

where V_1 = measured velocity of vibration

V_o = velocity at the threshold of annoyance

a_1 = measured acceleration of vibration

a_2 = acceleration of the threshold of annoyance

J = intensity of vibration in Pal units

Postlethwaite (1944) constructed frequency scales of equal vibration sensation, calling them Trams. Janeway (1950), after a comprehensive review of other tolerance studies, determined that comfort was a constant function of rate of change of acceleration from 1 - 6 Hz, of acceleration between 6 and 20 Hz and of velocity from 20 - 60 Hz. Dieckmann (1958) on the other hand, developed a weighting scale that defined comfort as a function of acceleration (1 - 6 Hz), velocity 6 - 20 Hz) and displacement (20 - 60 Hz), obviously one derivative away from those of Janeway. Using cross-modality matching of noise loudness and vibration intensity, Versace (1963) concluded that comfort was a function of rate of change of acceleration.

To summarize and critique, most of the studies reported used sinusoidal vibration in small laboratory studies and developed criteria that varied as much as 100 fold for perception (Allen, 1971). These studies, for the most part, were concerned with vehicle ride and tolerance. They generally agreed that comfort was frequency dependent and that the frequency range of approximately 4 - 8 Hz was most critical; generally ascribed to body member and whole body resonance frequencies.

ISO Standards

In 1970 the International Organization for Standarization published a guide for the evaluation of human exposure to whole body vibration. A new standard was published in 1974. In the introduction to the 1974 edition the authors state:

> "In view of the complex factors determining the human response to vibrations, and in view of the paucity of consistent quantitative data concerning man's perception of vibration and his reactions to it, this International Standard has been prepared first, to facilitate the evaluation and comparison of data gained from continuing research in this field; and, second, to give provisional guidance as to acceptable human exposure to whole body vibration. The limits proposed in this International Standard seem to be a fair compromise between the available data and should satisfy the need for recommendations which are simple and suitable for general application. These limits are defined explicitly in numerical terms to avoid ambiguity and to encourage precise measurement in practice. However, when using these criteria and limits it is important to bear in mind the restrictions placed upon their application."

The following delimits the scope and application of the standard:

> "This International Standard defines and gives numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz. It may be applied, within the specified frequency range, to periodic vibrations and to random or non-periodic vibrations with a distributed frequency spectrum. Provisionally, it may also be applied to continuous shock-type excitation insofar as the energy in question is contained within the 1 to 80 Hz band."

> "These limits are given for use according to the three generally recognizable criteria of preserving comfort, working efficiency, and safety or health. The limits set according to these criteria are named respectively in this International Standard the "reduced comfort boundary," "fatigue-decreased proficiency boundary," and the "exposure limit." For example, where the primary concern is to maintain the working efficiency of a vehicle driver or a machine operator working in vibration, the "fatigue-decreased proficiency boundary" would be used as the guiding limit in laying down vibration specifications or

in carrying out vibration control measures, while, in the design of passenger accommodations, the "reduced comfort boundary" should be considered."

"According to the criteria mentioned, these limits are specified in terms of vibration frequency, acceleration magnitude, exposure time, and the direction of vibration relative to the torso. This direction is defined according to the recognized anatomical axes of the human body."

The criterion most applicable for the present purpose is preservation of comfort. To obtain the vertical (ISO longitudinal) reduced comfort boundaries from the published fatigue-decreased proficiency boundaries, the acceleration values must be divided by 3.15 (10 db lower). For example, the acceleration limit in the 4 - 8 Hz range for reduced comfort based on 24-hour exposure would be approximately 0.0004 'g' RMS.

Allen (1971) has critized the 1970 standards on the following bases:

1. Short term exposure limits to vertical vibration are too lienient. He goes on to point out that the 4-minute reduced comfort boundaries are in the band of comfort of all, and even the intolerable region of some of the 13 laboratory studies he reviewed.

2. Limits of horizontal vibration above 3 Hz are probably too strict and should be set equal to those of vertical vibration.

3. Criterion limits are based on mean responses and do not reflect variability (standard deviations) of responses. This suggests that as many as 50% of individuals would be uncomfortable before the comfort level is exceeded.

4. The standards were based mainly on laboratory studies and it is possible that tolerance in the laboratory is higher than in the real world.

5. The standards do not allow for the possibility of additive or synergistic effects of vibration in more than one direction.

Griffin (private communication) has proposed as a reasonable limit for residential vibration .001 'g' RMS or down 30 dB from the 8-hour fatigue-decreased proficiency boundary. For offices the reduction would be 24 dB and for critical areas such as hospitals, down 36 dB. For residents this would place the limit 20 dB lower than the reduced comfort boundary proposed in the ISO standards. This is in line with the Reiher and Meister (1931) criteria and with the criteria used by the German courts (Splittgerber, 1969).

To accommodate vibration spectra (rather than discrete frequency vibration) the ISO Standards provide weighting factors relative to the frequency range of maximum acceleration sensitivity. These weights, when multiple by the acceleration in the respective frequency bands and summed over the significant components provides a single value of measured vibration intensity. The weighting factors, presented in Table 3 of the standards, are derived from the inverse of the boundaries provided by the Standards.

Tokita (1973) has described how an electronic network weighting procedure based on the ISO Standards has been implemented in Japan in connection with the consideration of vibration criteria and environmental regulations. The ratio of the output of the weighted network (a) to the standard ($a_o = 10^{-5}$ m/sec^2 or approximately .000001 'g') is then expressed in decibels as

$$L = 20 \cdot \log_{10}(a/a_o).$$

Tokita (1973) reported that complaints tended to be associated with vibration levels over 60 dB (approximately .001 'g') on the weighted acceleration scale. This weighted level was found to be induced in buildings 20 m away from the road edge in good construction and 80 m away from the Tokaido line railway express.

Fothergill (1973) used a method equivalent to the ISO weighting network and concluded that his work supported the concept. Jones and Saunders (1972) constructed a set of equal comfort curves for both men and women in unrestrained sitting positions. Their curves imposed more reduction on vibration levels for reduced comfort than those proposed in the 1970 ISO Standards. They further cautioned that the curves were based on mean responses of 60 subjects and that legislation should consider the 50% who were more sensitive to vibration annoyance.

To summarize, the 1974 ISO Standards provide a technique for weighting frequency components of random vibration to provide a single level that reflects the frequency dependency of human vibration response. The absolute value of this level that will reflect complaints of a population, however, must still be determined. There is some evidence to suggest that the ISO recommended levels are somewhat lenient, even for vehicle ride where vibration is expected and tolerated more. Further, the ISO Standards are based on mean response where, say, the lower 10th percentile of a population should be determined and would probably be more appropriate. Finally, the ISO Standards do not directly provide for increases or decreases in tolerances that may be associated with a myriad of other variables, some of which are outlined in the next section.

Other Variables That May Influence Vibration Tolerance

Given that it is possible to obtain a single value from a frequency weighting network, how can this value be related to the probability of complaints. A logical starting point might be to try to relate the probability of complaint to the daily probability of exceeding some specified level. In all likelihood, this probability would be influenced by a number of factors. Some candidate factors are given below.

Physical Variables: The architecture and condition of the building will undoubtedly influence the probability of complaints. Most of the reported vibration comfort criteria, discussed above, are based on steady state excitation. The transient nature of highway vibration using induced building vibration suggests that the influence of the dynamic characteristics of the buildings, especially damping, must be taken into account (Wiss and Parmelee, 1974).

Lenzen (1966) reported, based on experimental studies using steel joist - concrete slab floors, that when damping exceeds 5% of critical damping, individuals felt only initial impact. Below 3% critical, the response was similar to that of steady state. Between 3% and 5% critical, tolerance was greater than the steady state by a factor of 10.

Nelson (1971) suggests an extension of the Reiher and Meister formula to include a damping factor as follows:

$$A_o f = C_1 \zeta^n + C_2$$

where A_o = maximum displacement of the impact response

ζ = damping ratio (percent of critical)

Wiss and Parmelee (no date) fitted experimental data using the following equation to obtain a subjective response weighting parameter, R, as

$$R = 5.08(fA_o)^{0.265}/(\zeta)^{0.058}$$

R = 1, imperceptible vibration

R = 2, barely perceptible vibration

R = 3, distinctly perceptible vibration

Other physical variables, such as the absence of windows, would have to be considered separately. Climatic conditions could also influence response.

Environmental Variables: The combined effects of noise and vibration will probably interact to influence the probability of complaint although it is difficult to know in what manner. Sommer and Harris (no date), found a synergestic effect between high intensity noise and vibration. With respect to performance, Harris and Shoenberger (1970) reported that the effects of noise and vibration may be additive. Gurgnard (1971) reported that above 30 Hz human response to vibration merges with and becomes secondary to auditory stimuli.

Psychological Variables: Human response to any environmental stimulus are influenced by many psychological variables, few of which are understood with any degree of clarity.

a. Startle: If a building occupant knows when to anticipate vibration intrusion, he is less likely to complain than if the intrusion takes him by surprise. Two or three incidents above the comfort threshold per day at random time intervals are probably more likely to generate complaints than a constant level just at the comfort threshold level.

b. Adaption Level: A sudden increase in traffic density or the opening of a new highway should initially produce more complaints than in subsequent months because humans have a rather amazing capacity to adapt to various energy input levels. This type of response history is in line with field research into the effects of sonic boom (von Gierke and Nixon, 1972).

c. Time of Day: One might expect that intrusions at bedtime and in the early morning would be more likely to disturb sleep and to produce complaints. Griffin (personal communication), however, has suggested that the bed provides sufficient additional isolation so that criterion levels need not be reduced at night.

d. Dissonance: Once humans make a major decision they are more likely to attend to positive aspects resulting from the decision and less likely to search for or attend to negative aspects. Persons who moved knowingly and voluntarily into buildings that are subjected to noticeable vibration levels are less likely to complain than individuals already occupying buildings prior to the build-up of vibration problems.

e. Fear of Property Damage: Seeing objects in the building vibrate and detecting cracks in the walls and ceilings would most probably heighten complaints both from fear of property damage and fear of building collapse. Owners would probably be more attentive to property damage than tenants.

f. Urban Versus Rural Environment: Threshold of complaints should be associated with higher intensity levels in urban as opposed to rural environments, largely because of adaption levels.

g. Psychological Well Being of the Occupants: Stable and well adjusted occupants would probably complain less than a family, for example, in the middle of marital problems.

h. Psychological Well Being of the Community: In communities where there is considerable civil unrest or in time of national domestic crises one might anticipate more complaints.

i. Economic Status of Occupants: It is reasonable to expect members of a higher economic status, with more perceived influence and power, to complain more at a given vibration level above threshold (Zepler, Sullivan, Rice, Griffin, Oldman, Dickerson, Shepherd, Ludlow and Lange, 1973).

Summary

It is well established that human response to vibration is a function of magnitude, frequency, exposure time and direction of vibration relative to the human torso. Comfort and tolerance criteria almost all show the most sensitive levels in the 4 - 8 Hz range with gradual decreases in sensitivity on either side of this range. These conslusions, although based largely on laboratory studies of sinusoidal vibration and concerned mainly with vehicle occupants, are nevertheless sufficiently general to apply to the problem of building vibration.

The 1974 ISO Standards for the evaluation of human exposure to vibration, while probably deficient in some respects, represent a base of departure for future investigations, The weighting network proposed in the standards to account for the frequency dependency of human response to vibration is the most meaningful attempt yet to provide a single value related to human response to random vibration.

Although many have cited large discrepancies in reported comfort and tolerance criteria, it is probably realistic to view these discrepancies as reflections of the considerable variability of human response under varying conditions. No single value is going to adequately reflect the boundary between complaint and no complaint by building occupants. Some of the factors cited plus many others can be expected to influence the threshold of complaint.

It is recognized that the weighting network proposed in the 1974 ISO Standards are considered as providing a single vibration intensity value. This value could then be referenced to some selected value and reported in decibels. Based on field studies in troublesome areas the probability of complaint could then be related to the probability of complaint could then be related to the probability per day of exceeding a given dB level.

Survey data should be gathered on those physical, environment and psychological variables discussed and others relevant variables that may be uncovered. These data, when reduced, could provide, for example, a vibration susceptibility index based on an empirical weightings of the variables involved. Separate complaint probability curves could then be developed for several levels of vibration susceptibility.

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IMPACT FROM TRAFFIC-INDUCED VIBRATIONS

APPENDIX V

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FINAL REPORT

PREPARED FOR:

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
OFFICE OF RESEARCH
ENVIRONMENTAL DESIGN AND CONTROL DIVISION
WASHINGTON, D. C. 20590

APPENDIX V

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1.0 INTRODUCTION

The engineering analysis of traffic-induced vibration comprises four basic elements to describe the problem. These basic elements are:

- Pavement Loading
- Vehicle/Pavement Interaction
- Propagation of Ground Motion from the Highway
- Traffic Flow Model for Ground Vibration.

Each element is an integral part of the entire analysis. The final objective of the analysis is to formulate a complete model for the prediction of ground vibration induced by mixed traffic flows. An available technical base upon which to formulate directly such a model was totally absent from the literature at the initiation of the project. Hence, each element had to be formulated with the objective of integration into the overall traffic flow model and each element had to contain the significant parameters required to describe the problem. The available technical literature did, however, contain the basic ingredients upon which this engineering analysis is developed. (See Appendix I.)

For prediction of dynamic pavement loading, it was recognized that pavement surface roughness was the key aspect of the prediction problem. This analysis classifies pavement surface roughness as either a discrete bump or as a random surface roughness. The discrete bump is described by its height or depth relative to the pavement surface and its length in the direction of the moving tire. Based upon the model of a vehicle tire/suspension system, it is shown that the "impact factor" used by highway engineers may be scaled in general terms to "collapse" test data for different vehicles and different bump shapes. The estimation of impact factors (using the method of this analysis) is simple, quick, and accurate. This result is to be new. Random surface roughness is described by its amplitude power spectral density function. The random dynamic pavement loading resulting from the vehicle interaction with the random surface roughness of the pavement is estimated in terms of the static tire load and the mean-square dynamic load. These results are simple. Quantitative estimates of dynamic pavement loading, using the methodology of this analysis, may be easily obtained in a few minutes using a pocket calculator. The methodology relates dynamic pavement loading to the static load, the vehicle suspension system characteristics, vehicle speed and the random surface roughness description. In order to allow highway engineers to "relate" physically to the roughness power spectral density function, an approximate relationship of the roughness power spectral density to the Present Serviceability Rating (PSR) of the pavement roughness is presented. This result is sufficiently accurate to estimate both dynamic pavement loading and dynamic response of the pavement/subgrade system.

To estimate the dynamic response of the pavement/subgrade system, a model was formulated based upon a flexible slab resting on a single layer elastic subgrade. Both the slab and the subgrade are assumed to exhibit uniform mass and stiffness characteristics. The model considers the transfer of edge shear forces from the slab to the subgrade. These shear forces comprise the radiation stiffness and damping of the subgrade. Hence, the propagation of pavement dynamic loading to the subgrade and into the soil system surrounding the highway is simulated. All parameters derived using this approach are identical to design parameters used by highway engineers to establish thickness for rigid pavement design. This model was utilized to estimate the dynamic response of the pavement to both impulse loading and to random loading. The estimation procedure is simple. Using a pocket calculator, dynamic pavement acceleration response is easily estimated in a few minutes.

The propagation of vibration away from the highway considers the time-varying nature of the moving vehicle source and a stationary receiver location. To characterize this scenario, the concept of an equivalent vibration level is used. This concept is totally analogous to the equivalent sound level used in traffic noise analysis. Based upon the results of the analysis described above, the experimental program described in Appendix VI and the data available in the literature, a vehicle vibration source emission model is formulated. This model relates the pavement surface roughness, the vehicle speed, and the vehicle gross weight to the vehicle/pavement system as a source of environmental vibration.

Based upon the concept of the equivalent vibration level, a traffic flow vibration model is formulated. This model is identical in concept to the traffic flow noise models used for highway noise impact estimates. The traffic flow vibration model identifies heavy vehicles and rough pavement surfaces as the dominant source of traffic-induced vibration. Compared to traffic noise, however, the traffic flow vibration model is vastly simplified due to the nature of traffic-induced vibration problems. From a practical standpoint, one needs to consider only the pavement sections within 300 feet (91 m) of a receiver location. This is anticipated from the propagation model used in the theory, the Task B results (Appendix II), and the Task D results (Appendix VI). Hence, as a prediction model, the theory needs to consider only "infinite" roads as a vibration source. Alternately, the receiver is influenced only by the traffic-induced vibration generated in roadway sections in his immediate vicinity. The traffic flow vibration model is further simplified in that criteria available to evaluate both human perception and the potential for building damage relates to the vibration level and the number of repetitions of these levels. The model predicts that the peak vibration levels occur individually from the heaviest vehicles comprising the traffic flow. Hence, if the traffic flow comprises a mixture of vehicles (by weight) it is necessary to consider only the heaviest vehicles. Hence, the single event vehicle pass-by is the important consideration, not the traffic flow.

This Appendix is divided into sections describing the pavement loading, the vehicle-pavement interaction, the propagation of vibration from the highway, and the traffic flow model.

2.0 PAVEMENT LOADING

The functional design of highway pavements involves the study of soils and paving materials to ensure that the highway will carry the design loading under all climatic conditions. The design pavement loading is usually expressed in terms of a number of repetitions of wheel loading (by vehicle weight groups) required to induce pavement failure beyond the design life of the highway. For design purposes dynamic pavement loading is considered usually in terms of an "impact factor" specifying the maximum dynamic loading as a multiple of the static loading. For highway design, an impact factor of 1.2 is a good rule of thumb. That is, the maximum dynamic loading is taken to be 20% greater than the static loading (2-1)*.

Traffic-induced vibration is the effect of the dynamic response of a pavement/subgrade system to loading induced upon the pavement by the passage of a vehicle. The pavement loading comprises two components: a static component equal to the porportion of the vehicle weight carried by each wheel and/or axle and a dynamic component that varies as a function of suspension system, tire characteristics and vehicle speed. The objective of the analysis presented here is to determine the functional relationships between the vehicle parameters and pavement surface characteristics in order to estimate the pavement loading. The basic assumption underlying this anlaysis is that the pavement loading is independent of the pavement response to the loading. That is, the analysis of the pavement loading assumes that the pavement/subgrade is absolutely rigid and the description of the unloaded surface roughness is the only pavement/subgrade parameter influencing the loading.

The vehicle dynamic characteristics are determined using a lumped mass model representing the body mass, suspension system, and tire stiffness. Two classifications of highway surface roughness are considered: a discrete

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* Numbers in parenthesis denote references at the end of the Appendix.

bump model and a random surface roughness. The discrete bump model represents a specific definable surface irregularity such as a trench or highway joint. The random surface roughness is representative of irregularities that are distributed spatially over the pavement surface and can only be described in terms of statistical parameters.

The pavement loading is then determined for a vehicle responding to each class of surface roughness. For discrete bumps, the loading is expressed in terms of a shock spectrum which describes the peak loading as a function of bump shape, vehicle speed, and vehicle dynamic characteristics. For random amplitude road roughness, the pavement loading is obtained as a mean-square value that is a function of surface roughness parameters, vehicle dynamic characteristics, and vehicle speed.

2.1 VEHICLE DYNAMIC MODEL

The dynamic model selected for describing the vehicle is a two degree-of-freedom spring-mass system with base motion forcing input (2-2). The model is taken as a basic tire/suspension system supporting a portion of the total vehicle mass. The vehicle model is illustrated in Figure 2.1-1 along with a representative frequency response function of the model.

All parameters related to the vehicle are assumed to be linear time-invariant quantities. This assumption is not, strictly speaking, accurate since elements representing the suspension stiffness and the tire stiffness can respond with nonlinear load deflection characteristics. The assumption of linearity is made in order to establish design-oriented results in an explicit form. The basic vehicle model is utilized to formulate a traffic flow model rather than focus detailed attention upon specific vehicle parameters.

2.1.1 Equations of Motion

For the vehicle model illustrated in Figure 2.1-1, the equations of motion of the system are obtained in terms of the system parameters and the relative

Static Tire Load = $W_b + W_s = W_T$

Body Weight = $W_b = m_b g$; Suspension Weight = $W_s = m_s g$

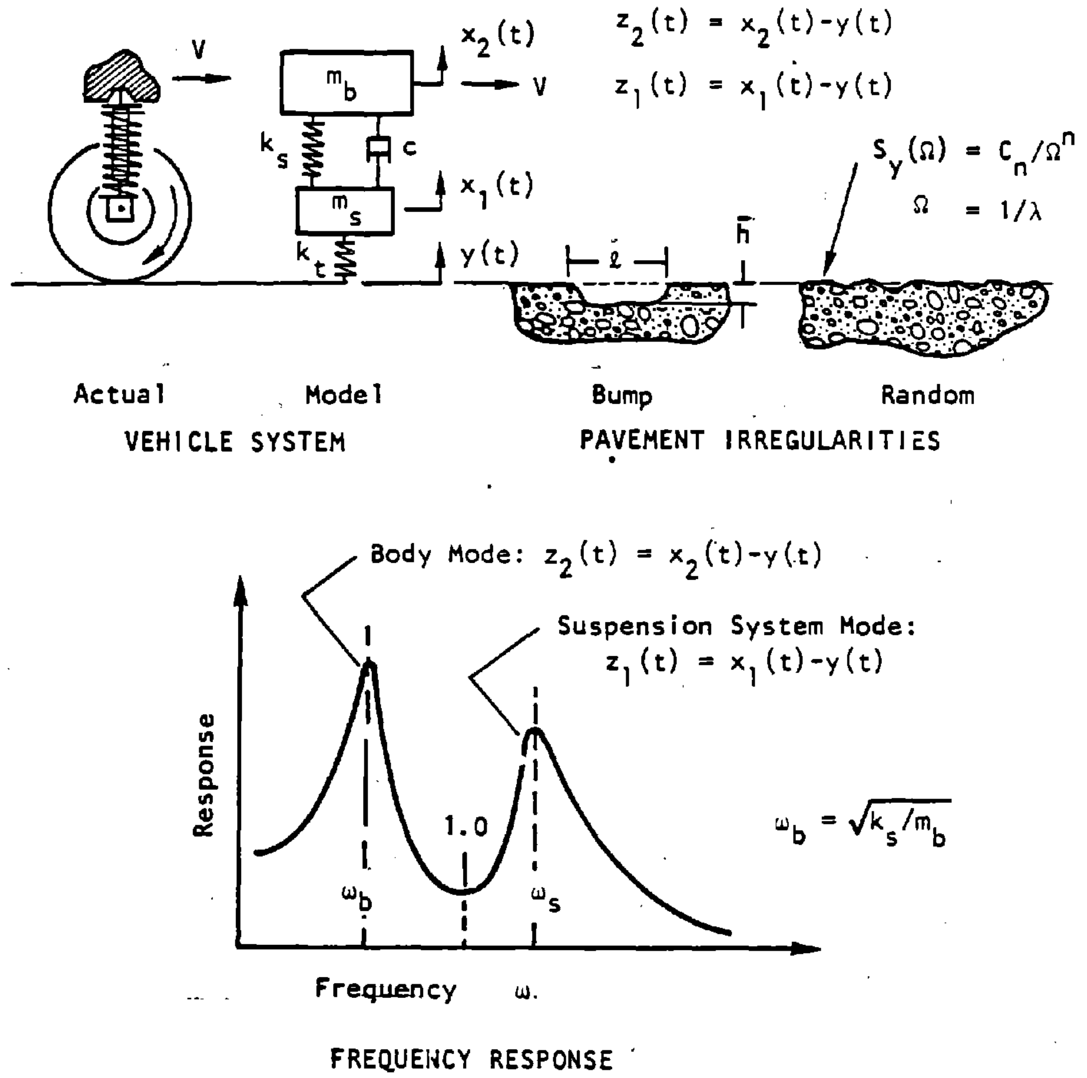


FIGURE 2.1-1 VEHICLE MODEL AND SYSTEM FREQUENCY RESPONSE

displacements between the base and the lumped masses as

$$m_b\ddot{z}_2(t) + c\dot{z}_2(t) - c\dot{z}_1(t) + k_s z_2(t) - k_s z_1(t) = -m_b\ddot{y}(t) - W_b \quad (2.1\text{-}1a)$$

$$m_s\ddot{z}_1(t) - c\dot{z}_2(t) + c\dot{z}_1(t) - k_s z_2(t) + (k_s+k_t)z_1(t) = -m_s\ddot{y}(t) - W_b \quad (2.1\text{-}1b)$$

where y(t) is the time varying displacement input to the system through the tire (modeled as a linear spring of stiffness, k_t) and the overdots denote time derivatives.

The total relative displacements $z_1(t)$ and $z_2(t)$ are comprised of a static component and a dynamic (function of time) component. The static components are due to the constant weights W_b and W_s appearing in the right-hand side of Equation (2.1-1). The total relative displacements are expressed in terms of the static and the dynamic components as

$$\begin{aligned} z_1(t) &= \bar{z}_1(t) + z_{1s} \\ z_2(t) &= \bar{z}_2(t) + z_{2s} \end{aligned} \quad (2.1\text{-}2)$$

where the overbar denotes the dynamic component and the subscript s denotes the static component.

The form utilized for the equations of motion in terms of the relative displacement of the masses is convenient since the pavement loading, as described by the model, is simply the product $k_t z_1(t)$.

2.1.2 Solutions to the Equations of Motion

Solutions to the equations of motion (2.1-1) are obtained either by direct integration of the equations of motion if the input forcing or base motion y(t) is known explicitly or, more conveniently, in the frequency domain if the base motion is known in terms of a mean-square spectral density function.

Direct integration of the equations of motion is utilized for surface irregularities of definable shapes such as bumps (2-2, -3). Frequency analysis of the vehicle dynamic model is most conveniently utilized for random road roughness forcing since the base motion input is known only in terms of a mean-square spectral density function of the surface roughness (2-2, -4, -5, -6, -7).

The system frequency response function will be discussed first since this development will illustrate how the vehicle model can be idealized as two single degree-of-freedom oscillators. For the discrete bump excitation it is most convenient to consider single degree-of-freedom systems since many excitation or bump shapes have been previously investigated (2-3).

2.1.2.1 System Frequency Response Functions

For convenience, the static components of the total relative displacement are removed from the equations of motion by substituting Equation (2.1-2) into Equation (2.1-1) to obtain two sets of equations. The static equations comprise a pair of linear equations that are solved for the static relative displacements, z_{1s} and z_{2s}. The results are (See Figure 2.1-1):

$$\begin{aligned} z_{1s} &= -W_b/k_s - W_T/k_t \\ z_{2s} &= -W_T/k_t \end{aligned} \qquad (2.1\text{-}3)$$

The dynamic equations or equations of motion are identical to Equation (2.1-2) with the weight tons on the right hand side removed. The solution of the coupled equations of motion are required in order to estimate the pavement dynamic loading. The objective is to obtain the system frequency response function for the random vibration analysis. This is easily achieved using standard technique (2-7). The results are, however, complicated. As described in Section 2.3.2, the vehicle response may be considered as two uncoupled motions described by the body motion, $z_2(t)$, and the suspension system motion. This assumption was evaluated numerically for representative data (2-2) and is appropriate for the problem. For the uncoupled equation of motion, the resulting frequency response functions are:

$$Z_1(\omega) = \omega^2 \overline{Z}_1(\omega)\overline{Y}$$
$$Z_2(\omega) = \omega^2 \overline{Z}_2(\omega)\overline{Y} \qquad (2.1\text{-}4)$$

where $\overline{Z}_1(\omega) = [\omega_s^2 - \omega^2 + i2\zeta\omega_s\omega]^{-1} \qquad i=\sqrt{-1}$

$\overline{Z}_2(\omega) = [\omega_o^2 - \omega^2 + i2\zeta\omega_o\omega]^{-1}$

$\omega_b^2 = k_s/m_b$ is the uncoupled body frequency

$\omega_s^2 = (k_s+k_t)/m_s$ is the uncoupled suspension frequency

$\overline{Y}$ is the amplitude of the surface roughness at frequency ω

The function $Z_1(\omega)$ represents the total relative displacement (in the frequency domain) of the axle to the pavement surface. The frequency response fucntion of the total pavement load is the tire stiffness times $Z_1(\omega)$. The result is:

$$P(\omega) = k_t \cdot Z_1(\omega) = k_t\omega^2\overline{Z}_1(\omega)\overline{Y} \qquad (2.1\text{-}5)$$

Because of the assumption of uncoupled motion, the pavement loading frequency response function, $P(\omega)$, is defined in terms of the suspension system only. The total static weight, W_T, is constant. The tire stiffness, k_t, is the stiffness at the tire load W_T.

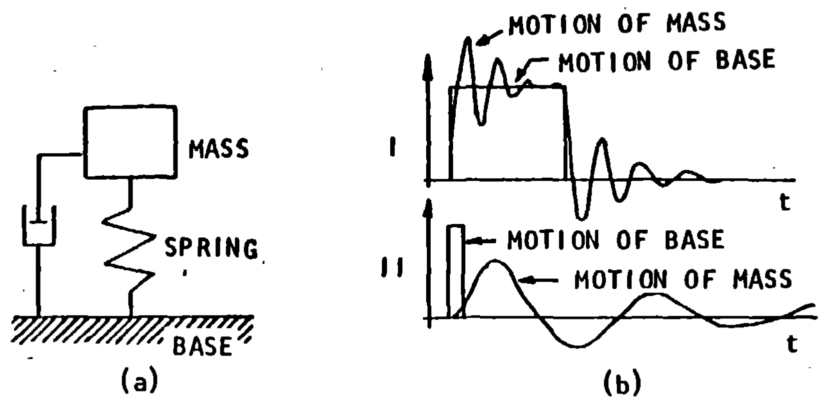
2.2 PAVEMENT SURFACE ROUGHNESS

Two basic types of pavement surface roughness are considered for this analysis: discrete bumps and random amplitude surface roughness. In practice, discrete bumps represent locaized pavement distress at a point on a highway (2-8) and are modeled as a known irregularity shape such as a step, ramp, or trench discontinuity in the pavement surface. Peak instantaneous amplitude of the impact loading is to be estimated. Random amplitude surface roughness is representative of irregular pavement surfaces distributed over a length of pavement such as corrugations, cracking, or simply poor paving. For random surface roughness, the estimation of the mean-square pavement loading resulting from the passage of a vehicle is required.

2.2.1 Discrete Bumps

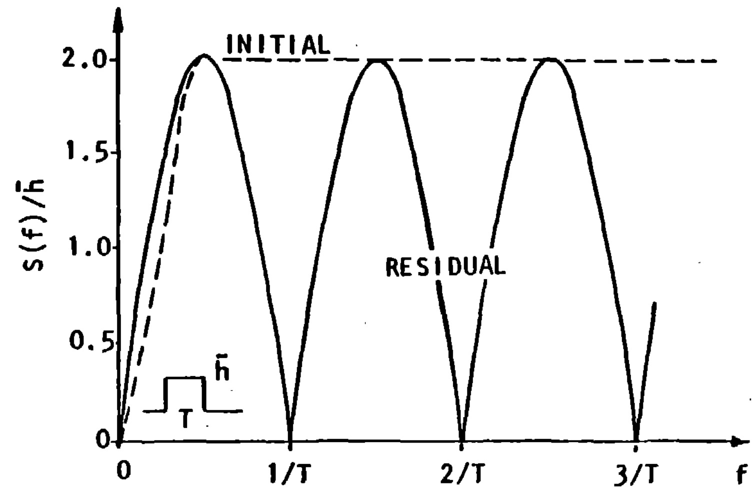
Typical mathematical models for discrete bumps are presented in Figure 2.2-1. The bump parameters are the height and length of the shape (enclosed area of the shape cross-section is commonly used for comparing different shapes (2-3)). The important aspect to realize is that the bump shape defines a time dependent forcing function on the vehicle that occurs in the time era $0 \leq t \leq \ell/V$ and the vehicle will respond to the forcing for $t \geq 0$ where t is measured from the leading edge of the bump. Depending upon the vehicle speed and the bump geometry, the maximum peak loading may or may not occur while the vehicle's tire is on the bump.

Figure 2.2-2 presents typical experimental results for describing the vehicle "impact factor" for a vehicle traversing a plank irregularity (2-9) and shapes representative of airfield landing lights (2-10). For the plank irregularity, the impact factor is plotted versus distance from the plank indicating the effect of vehicle "bounce". For the landing light data, maximum values of the impact factor are plotted versus vehicle speed. Here, the impact factor is taken as the ratio of dynamic loading to static loading. These references and the work by Whittemore (2-2) also discuss effects of tire pressure, vehicle spring stiffness, and tire enveloping the bump.

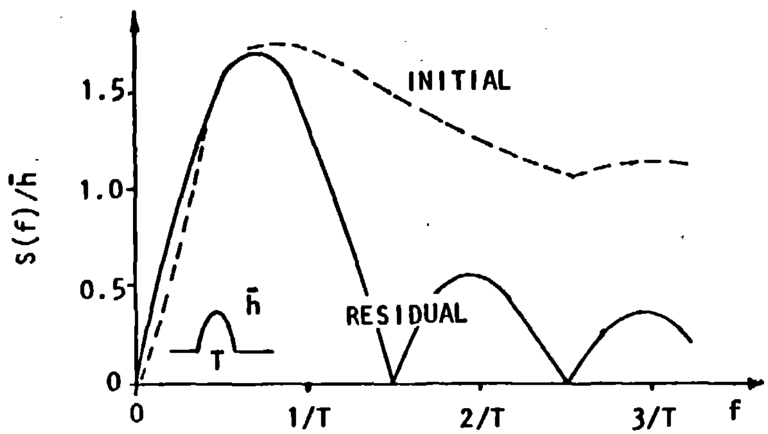


RESPONSE OF A SINGLE DEGREE-OF-FREEDOM SYSTEM TO SHOCK EXCITATION

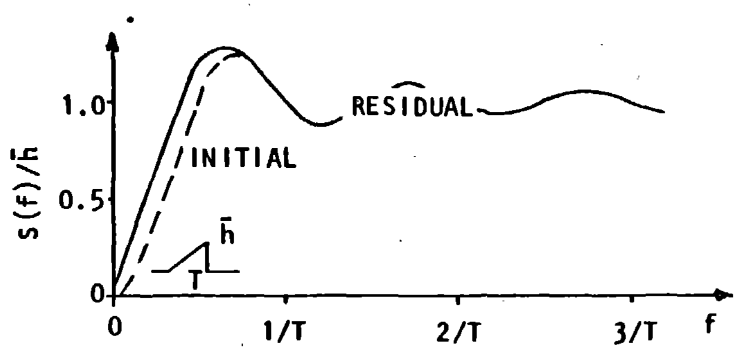
$\bar{h}$ = Bump Height ℓ = Bump Length
$T = \ell/V$ V = Vehicle Speed



SHOCK SPECTRA FOR A RECTANGULAR SHOCK PULSE

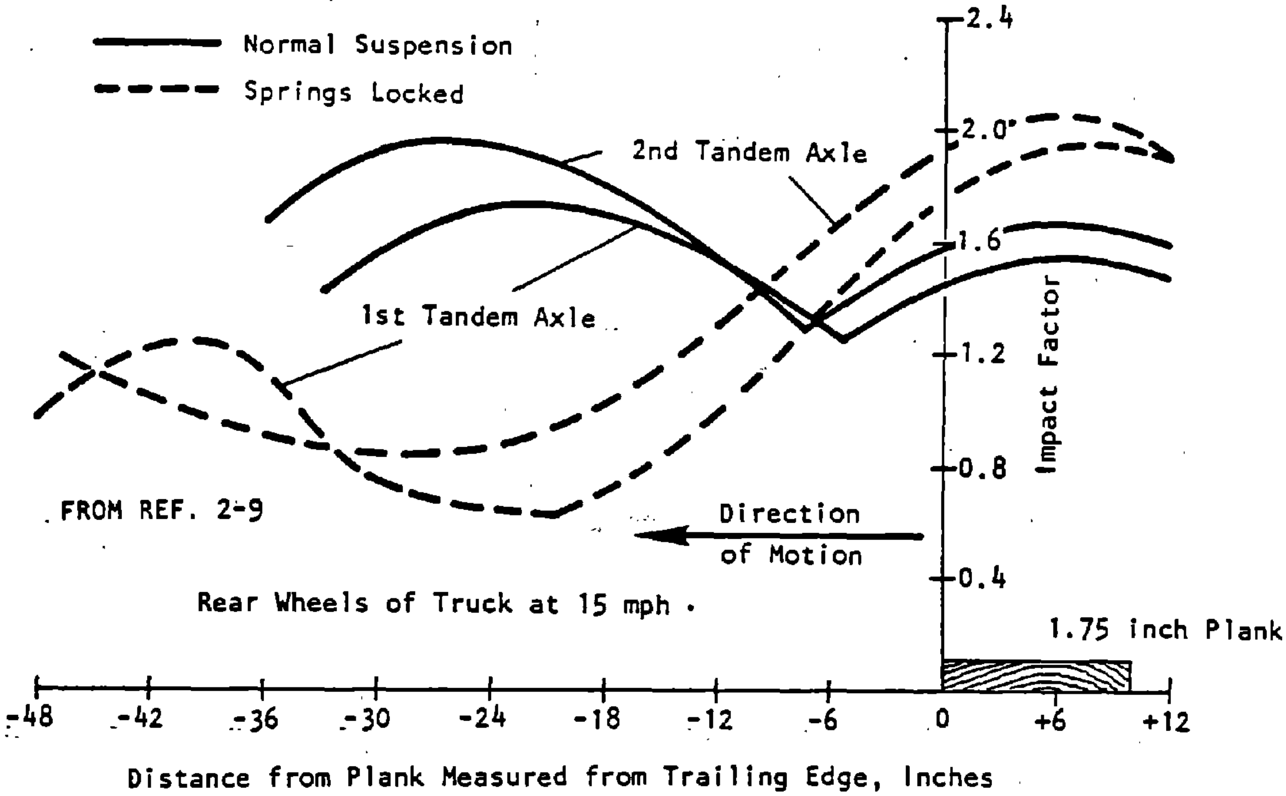


SHOCK SPECTRA FOR A HALFSINE SHOCK PULSE

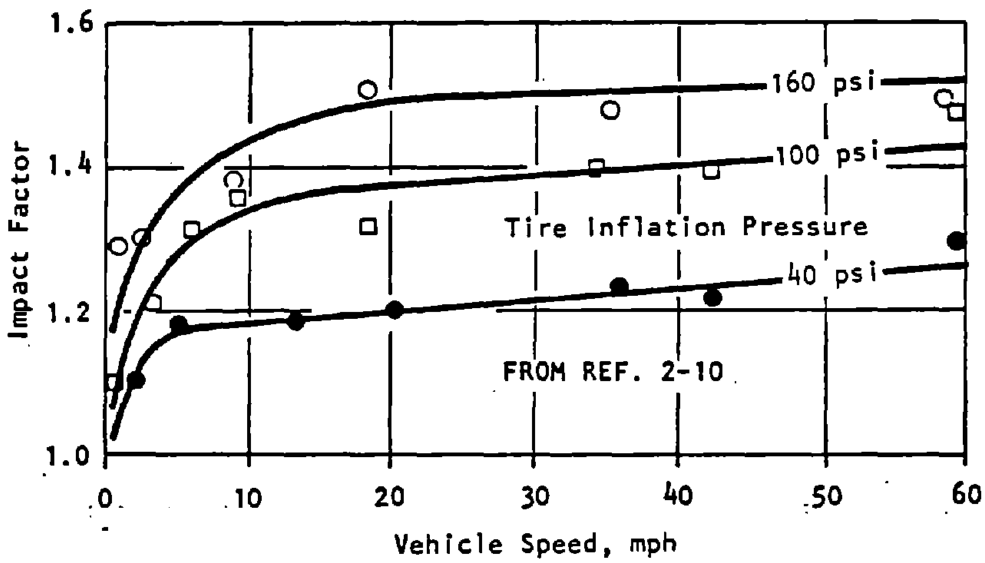


SHOCK SPECTRA FOR A FINAL PEAK SAWTOOTH PULSE SPRING

FIGURE 2.2-1 MATHEMATICAL MODELS OF DISCRETE BUMPS



(a) Impact Factor Versus Distance



(b) Impact Factor Versus Speed

FIGURE 2.2-2 EXPERIMENTAL IMPACT FACTOR DATA

For the purposes of estimating peak amplitudes of ground motion induced by discrete surface irregularities, it is important to note that the maximum dynamic loading generally ranges between 1.0 and 2.0 times the static loading. The basic parameters governing the impact loading are the vehicle speed, vehicle suspension system natural frequencies, tire stiffness, and the bump geometry (2-2, -9, -10, -11).

The basic relationships between the parameters can be described in terms of transient response spectra for the vehicle dynamic system. For this purpose, the shock spectrum of the vehicle dynamic system is the common format used (2-3), and for estimating the effect of the bump upon pavement loading, the maximum absolute value of the distortion of the effective spring of the vehicle dynamic system at any time as a result of the vehicle passing over a bump is the relevant response quantity. This response quantity, called the "maximax" distortion, is plotted against the ratio of the time that the force acts on the vehicle to the natural period of the vehicle's suspension system. Typical shock spectra for a single degree-of-freedom system are presented in Figure 2.2-3 for three bump shapes compared on the basis of equal shape area $\bar{h}\,\tau/2$ where $\bar{h}$ is the bump amplitude and τ is the pulse time or time required for the vehicle to traverse the bump. For a bump of length ℓ and a vehicle traveling at speed V, the pulse time, τ, equals ℓ/V. Hence, it is seen from Figure 2.2-3 that for a given bump shape and specific vehicle, vehicle speed alone determines the dynamic loading with the indication that increasing speed (decreasing τ) may actually decrease the pavement loading. The maximum dynamic pavement loading is then the product of the impact factor times the bump height.

A common method for inducing vibration in pavements has been to pass a heavy vehicle over a plank or ramp placed across the highway (2-9, -11, -12). Although this approach is in common use, it has not been standardized as a technique for evaluating either pavement response or the transmission of vibration from the bump location to a distant receiver location.

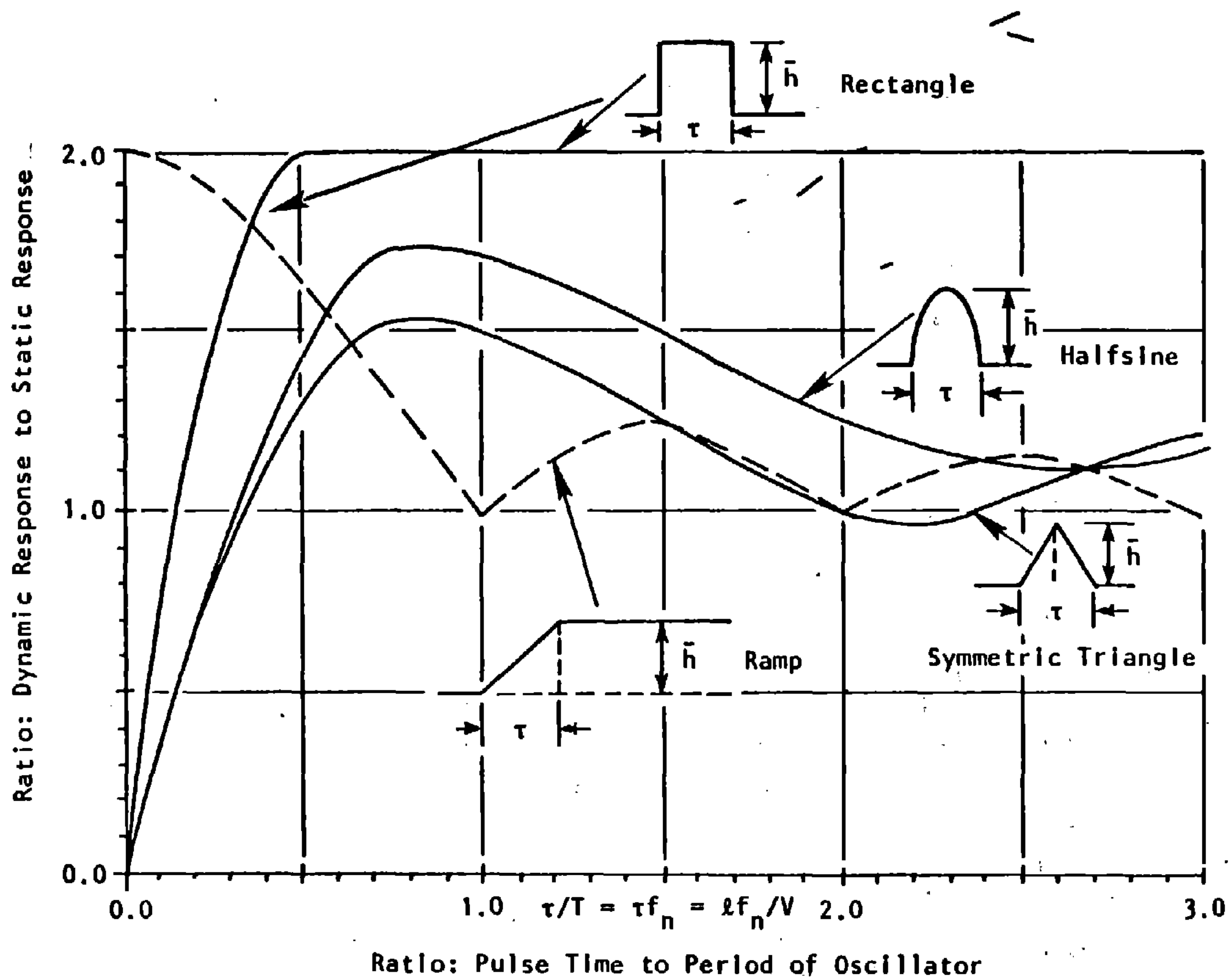


FIGURE 2.2-3 SHOCK SPECTRA

2.2.2 Random Surface Roughness

Based upon the work of previous investigators, typical road surfaces may be represented as realizations of random processes. (See References 2-2, -4, -5, -13, -14, -15, -17). For this idealization, it is assumed that the surface is void of large irregularities such as discrete bumps. Dobbs and Robson (2-13) have shown that road surfaces may be considered as realizations of homogeneous and isotropic two-dimensional Gaussian random processes. Hence a single direct spectral density function provides a surface description which is sufficient for multi-track vehicle response analysis.

Spectral density measurements of road surface roughness have been conducted by numerous investigators (2-2, -4, -13, -17) so that a common description of surface roughness has evolved. The mathematical expression for the displacement spectral density function is taken in the form

$$S_y(1/\lambda) = C_n/(1/\lambda)^n \qquad (2.2\text{-}1)$$

where λ is the roughness wavelength.
C_n is a constant

The engineering units of the roughness spectral density function are typically expressed as length squared per cycle per unit length or length cubed per cycle.

The mean-square surface roughness (units of length squared) is estimated by integrating Equation (2.2-1) between two wavelengths ($\lambda_1 < \lambda_2$) to obtain

$$d^2 = C_n \left[\lambda_2^{n-1} - \lambda_1^{n-1} \right] / (n-1) \quad \text{, units length squared} \qquad (2.2\text{-}2)$$

The result given in Equation (2.2-2) is the mean-square surface roughess amplitude contained between the two roughness wavelengths. Reference 2-13 presents another form of Equation (2.1-1) using a two segment or dual slope curve. From Equation (2.2-2), it is seen that C_n is proportional to the mean-square surface roughness amplitude per unit wavelength. Typically, the numerical value of the exponent n is quite close to 2.

Equation (2.2-1) expresses the surface roughness spectral density in terms of roughness wavelength. For the vehicle response problem, it is necessary to express $S_y(1/\lambda)$ as a function of frequency. To do this, one requires the mean-square roughness in an internal $\Delta(1/\lambda)$ to be equal to the frequency interval $\Delta\omega$. Further, the frequency is related to the roughness wavelength and the vehicle speed. Hence, the pavement surface roughness spectral density function in terms of frequency is

$$S_y(\omega) = S_y(1/\lambda)/V = (2\pi)^{n-1} C_n V^{n-1}/\omega^n \cdot \qquad (2.2\text{-}3)$$

$\omega = 2\pi V/\lambda$

V is the vehicle speed.

To obtain an estimate of the roughness spectral density function in terms of a more commonly recognized highway design parameter, the results of Reference (2-17) were used. These results were in the form of a statistical analysis aimed at relating the surface roughness power spectral density function to the Present Serviceability Rating (PSR) descriptor. The results, however, were tabulated only for the PSR ranges of 2.0 to 2.5 and 4.0 to 4.5. Based on these results, the tabulated data were plotted in the form of Equation (2.2-1). Since the data of Reference (2-17) were for intervals of the PSR index, straight lines were drawn through the data to obtain two curves of constant PSR. These curves were spaced 8 dB apart based upon the data of Reverence (2-17). The spectral density values at a wavelength of 43.2 feet (13.2 m) were used to determine the appropriate constant relating PSR to the spectral density. It was assumed that the exponent n was equal to 2.0. The results of this approximation were to obtain an estimate of the constant, C_2, in terms of a constant value of PSR. The approximation is:

$$C_2 = 10^{-(PSR+13.19)/2.503}, \text{ ft/cycle} \qquad (2.2\text{-}4)$$

This result is presented in Figure 2.2-4 with the tabulated data of Reference (2-17) plotted to indicate the approximation. It was recognized that the result of Equation (2.2-4) might be of unknown accuracy. To attempt an "audit" of the approximation, the results of Equation (2.2-4) were compared to other reported studies documenting pavement roughness power spectral density results. Based upon the data in Appendix G of Reference 2-2, values of C_n were estimated for the nine road sections documented. Using the approximation of Equation (2.2-4), values of PSR were obtained. The results of these comparisons are presented in Table 2.2-1. It is evident that the approximation of Equation (2.2-4) yields an appropriate rank ordering of the "ride quality" of the road section. A further "audit" of the approximation was made using the estimate of mean-square surface roughness given by Equation (2.2-2). The estimates seemed to agree with data reported in the literature. Hence, the results of Reference 2-17 agree with the results of Reference 2-2 relative to "ride quality" based uopn the above approximation.

2.3 VEHICLE RESPONSE TO ROAD SURFACE ROUGHNESS

Pavement loading is induced as a result of a vehicle passing over a surface irregularity. As presented in Section 2.2, surface irregularities are taken as definable shapes or as random roughness described by a spectral density function. To obtain an engineering approximation for the dynamic pavement loading, it is assumed that the pavement is absolutely rigid in estimating vehicle response and the resulting pavement loading. Consideration of an elastic pavement responding to the dynamic loading of a vehicle involves the consideration of a nonlinear spring coupling the vehicle mass with the effective mass of the soil (2-14, -15). Hence, the assumption of a rigid pavement for the purpose of estimating pavement loading is made in order to preserve the linearity of the problem. This assumption appears reasonable since available experimental data indicates that linear pavement response to moving loads can be expected for normal wheel loading encountered on highways (2-16).

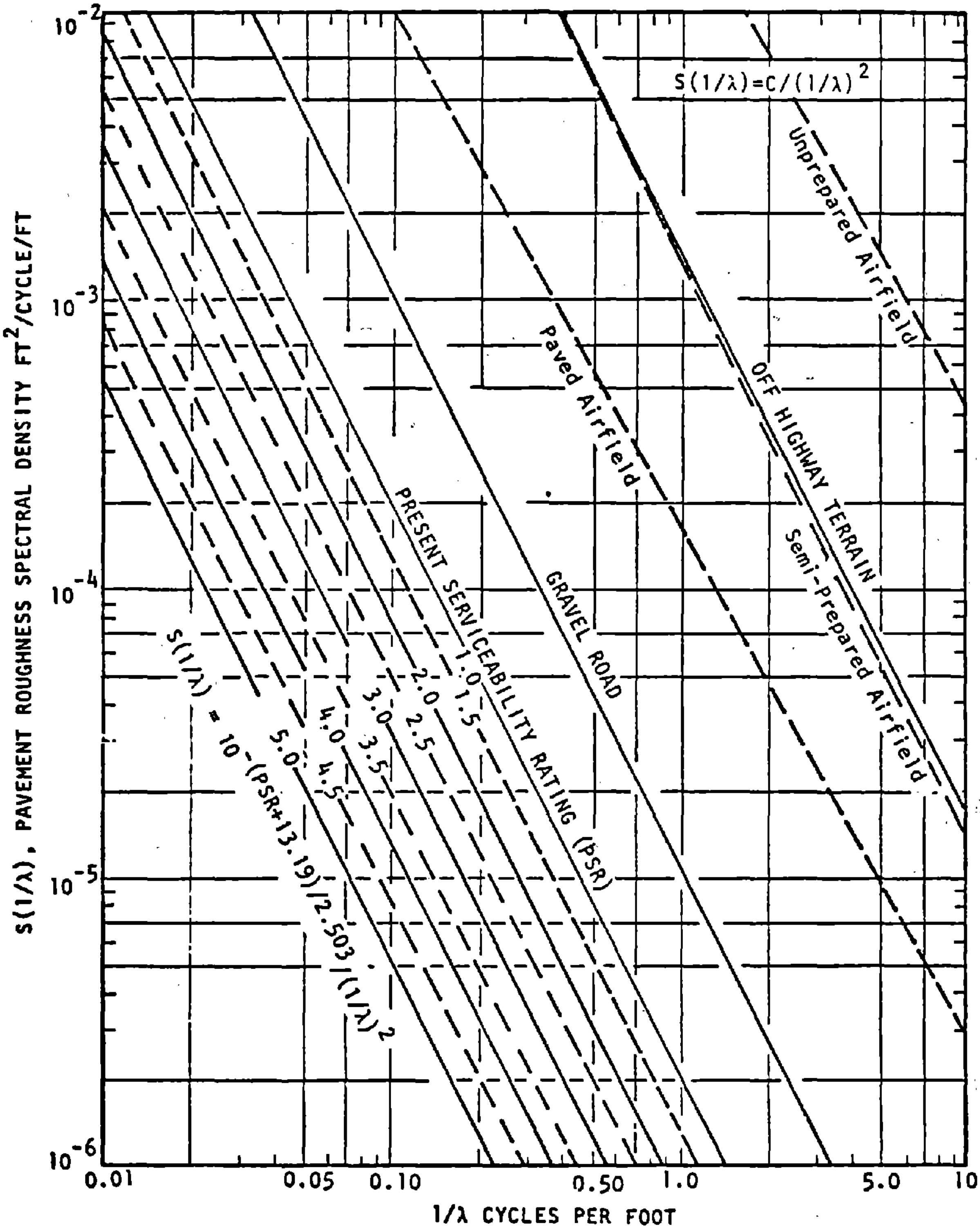


FIGURE 2.2-4 PAVEMENT ROUGHNESS POWER SPECTRAL DENSITY FUNCTIONS

TABLE 2.2-1

COMPARISON OF APPROXIMATE PSR VALUES
TO MEASURED ROAD PROFILE POWER SPECTRAL DENSITY FUNCTIONS

Data from Reference 2-2, Appendix G

Road Section	Pavement Type	"Roughness"	BPR Roughometer Roughness in 1 mile	Estimated Value of C_2, ft-cycle	PSR Estimate (Eqn. 2.2-4)
I-75	Rigid	Good	118	$1.4 \cdot 10^{-7}$	4.0
I-696	Rigid	Fiar	149	$2.4 \cdot 10^{-7}$	3.0
M-50	Rigid	Poor	176	$4.0 \cdot 10^{-7}$	2.8
M-52	Flexible	Good	92	$8.0 \cdot 10^{-8}$	4.6
M-247	Flexible	Fair	169	$4.0 \cdot 10^{-7}$	2.8
M-138	Flexible	Poor	249	$1.0 \cdot 10^{-6}$	1.8
M-53 NB	Overlay	Good	128	$8.0 \cdot 10^{-8}$	4.6
M-53 SB	Overlay	Fair	154	$4.7 \cdot 10^{-7}$	2.8
M-59	Overlay	Poor	225	$8.0 \cdot 10^{-8}$	2.1

2.3.1 Vehicle Response to Discrete Bumps

In order to obtain functional relationships between vehicle parameters and bump parameters for the purpose of estimating the pavement loading induced by a vehicle passing over a bump, the concept of a shock spectrum is used (2-3). The response quantity obtained is the maximum peak dynamic load. It is common practice in highway design to express the peak dynamic loading in terms of an impact factor defined as the ratio of the maximum peak dynamic load to the static load (2-1).

As described in Section 2.2.1, the significant bump parameters are the bump height, $\bar{h}$, and the bump length, ℓ. The significant vehicle parameters are the vehicle speed, V; the vehicle static wheel load, W_T; the tire stiffness, k_t; and the vehicle suspension system natural frequency, f_s. From a practical standpoint, it is known that except for controlled field tests one can only generally describe a discrete bump and that if an explicit shape is assumed, one can expect that tire enveloping will result in an unknown forcing of the tire and suspension system (2-2). Hence, an approximate model for estimating the dynamic loading has been selected that reflects experimental results.

By reviewing available experimental data (2-2, -9, -10, -11) and analytical results (2-3), the peak dynamic loading is modeled as the response of a one degree-of-freedom vehicle model to a half-cycle sine wave base motion displacement forcing. The amplitude of the base motion is taken as the bump height and the duration of the forcing is taken as the time required for the vehicle to pass over the bump. This model was selected since it apparently exhibits the characteristics of the experimental data and results in rather simple analytical expressions.

Using this approach, the maximum dynamic loading resulting from a vehicle traversing a bump of length ℓ at a velocity V is obtained in terms of three expressions dependent upon the vehicle speed. The maximum dynamic loading is expressed as

$$|P_{max}| = k_t\bar{h}/(1-v) \qquad 0 \leq V \leq \bar{V}/3 \qquad (2.3\text{-}1a)$$

$$|P_{max}| = k_t\bar{h}\cdot SIN[2\pi v/(1+v)]/(1-v) \qquad \bar{V}/3 \leq V \leq \bar{V} \qquad (2.3\text{-}1b)$$

$$|P_{max}| = 2k_t\bar{h}\cdot v\cdot COS(\pi/2v)/(v^2-1) \qquad V \geq \bar{V} \qquad (2.3\text{-}1c)$$

where $\bar{h}$ is the bump height

k_t is the tire stiffness

V is the vehicle speed

ℓ is the bump length

f_s is the suspension system natural frequency

$v = V/\bar{V}$ is the ratio of the vehicle speed to the characteristic speed

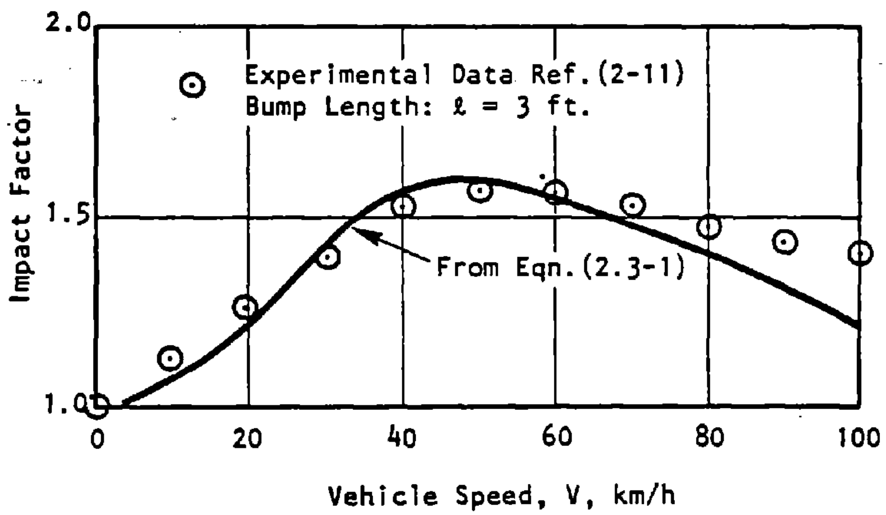
$\bar{V} = 2\ell f_n$ is a characteristic vehicle speed

The parameter $\bar{V}$ represents the vehicle speed at which the forcing period ℓ/V equals the natural period $T = 1/f_s$ of the suspension system. The impact factor is obtained by dividing both sides of Equation (2.3-1) by the static wheel loading, W_T.

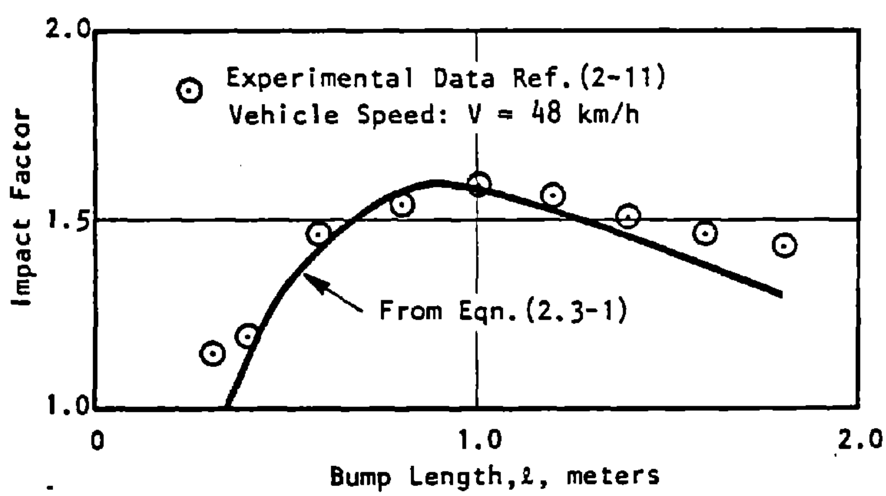
Using data presented by Potter (2-9) and Whiffin and Leonard (2-11), the results of Equation (2.3-1) are compared to experimental data in Figure 2.3-1. Figure 2.3-1a presents a plot of impact factor versus vehicle speed for a vehicle (truck) passing over a trench-shape bump. Figure 2.3-1b presents a plot of impact factor versus trench width, ℓ, for constant vehicle speed. In both cases it is seen that the agreement between Equation (2.3-1) and the experimental data is good. The results of Equation (2.3-1) are presented in dimensionless form in Figure 2.3-2 where the vertical axis is defined as the ratio of the maximum loading to the static force amplitude $k_t\bar{h}$.

The data associated with the comparison in Figure 2.3-1 is as follows:

Suspension System Natural Frequency: f_s = 12 Hz.
Vehicle Speed: V = 48 km/h = 44 ft/s (Figure 2.3-1b)
Bump Height: $\bar{h}$ = 25 mm = 1.0 inch
Bump Length: ℓ = 914 mm = 3.0 ft (Figure 2.3-1a)
Tire Stiffness: k_t = 4700 lb/in
Tire Static Load: W_T = 5200 lb



(a) Impact Factor versus Vehicle Speed



(b) Impact Factor versus Bump Length

FIGURE 2.3-1 COMPARISON OF PREDICTED AND EXPERIMENTAL VALUES OF PAVEMENT LOADING IMPACT FACTORS: DATA FROM REF.(2-11)

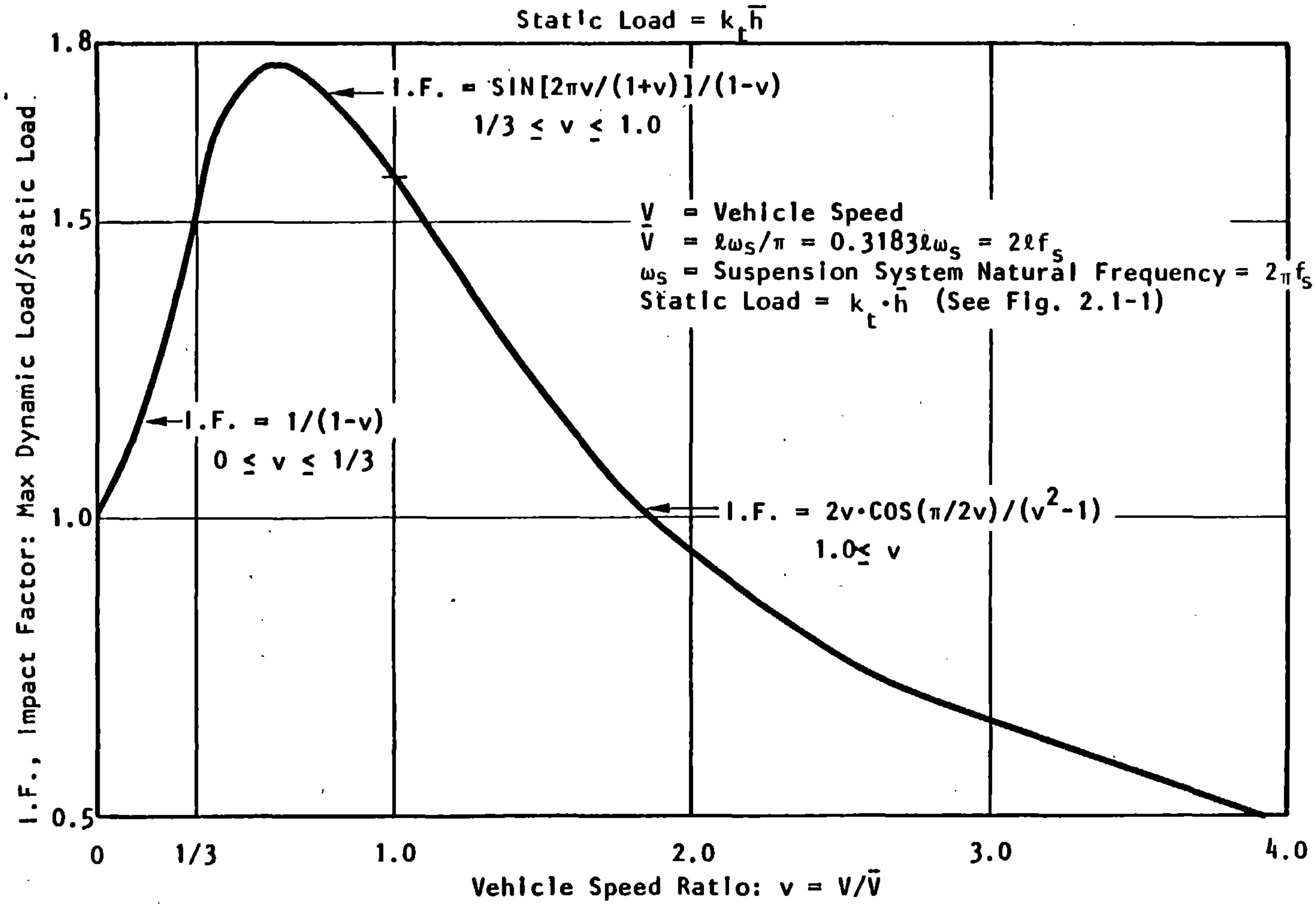


FIGURE 2.3-2 IMPACT FACTOR VERSUS NORMALIZED VEHICLE SPEED

2.3.2 Vehicle Response to Random Surface Roughness

The pavement loading resulting from a vehicle moving along a road comprises a static load and a dynamic load. The static load is a downward force resulting from the vehicle weight being transferred through the tire to the pavement. The dynamic load is the fluctuating or time varying component of the total load. The dynamic load is a result of the random surface roughness forcing the vehicle and the suspension system into random motion. The resulting random deflection of the tire about its statically loaded position is the mechanism by which the random pavement load is generated.

The total pavement loading to be estimated is taken as a random process with a constant mean value equal to the static loading, W_T, and a time-varying or dynamic component. Assuming that the random loading is ergodic (2-7), the pavement loading power spectral density function is expressed in terms of the frequency response function of the loading given by Equation (2.1-5) and the pavement surface roughness spectral density function given by Equation (2.1-5) as:

$$S_p(\omega) = k_t^2 \omega^4 \overline{Z}_1(\omega) \overline{Z}_1^*(\omega) S_y(\omega) \qquad (2.3\text{-}4)$$

where $\overline{Z}_1^*(\omega)$ is the complex conjugate of $\overline{Z}_1(\omega)$.

The result of Equation (2.3-4) assumes that the dominant component of the dynamic loading is a result of the vehicle tire/suspension system motion. For a vehicle traversing a pavement with random surface roughness, the roughness wavelengths causing the excitation are estimated in terms of the excitation frequency as indicated in Equation (2.2-3). Based upon the experimental data in Appendix VI, it appeared that the range of frequencies associated with traffic-induced vibration were from 8 Hz. to 15 Hz. This frequency range appears to correspond with the vehicle suspension system frequency, ω_s, given in Equation (2.1-4). The available data for evaluating the vehicle vibration response is presented in Table 2.3-1.

TABLE 2.3-1

VEHICLE WEIGHT, SUSPENSION, AND TIRE DATA: HALF AXLE DATA

Vehicle Parameter	Parameter Symbol	Units	"MANDATOR" Vehicle (TRRL 580)*	Test Vehicle No. 1 Loaded (NCHRP 105)*	Test Vehicle No. 1 Unloaded (NCHRP 105)*
• Mass and Weight Data					
Body Mass	M_b	$lbf \cdot s^2/in$	13.704	21.2	13.47
Suspension Mass	M_s	$lbf \cdot s^2/in$	1.919	3.1	3.1
Total Mass	M_t	$lbf \cdot s^2/in$	15.623	24.3	26.57
Body Weight	W_b	lbf	5291.	8185.	5201.
Suspension Weight	W_s	lbf	740.8	1197.	1197.
Total Weight	W_t	lbf	6031.8	9382.	6398.
• Stiffness Data					
Suspension Stiffness	k_s	lbf/in	1427.5	2500.	2500.
Tire Stiffness	k_t	lbf/in	8930.7	16,000.**	16,000.*
• Damping Data					
Shock Absorber Dampling	c_s	$lbf \cdot s/in$	22.8	50.0	50.0
Tire Damping	c_t	$lbf \cdot s/in$	5.71	12.5(Est.)	12.5(Est.)

* Report Reference

** Dual Tires

Assuming that the vehicle dynamic loading occurs at the suspension system frequency, ω_s, and that the system is lightly damped (ζ on the order of 0.2 or less) the mean-square value of the total pavement loading is obtained from Equation (2.3-4) as:

$$<P^2(t)> = W_T^2 + C_n V^{n-1} k_t^2 (W_b/W_s)^{(1-n)/2} (f_b/f_s)^{3-n} / (8\pi\zeta^2 f_s{}^{n-1}) \qquad (2.3\text{-}5)$$

For an index n=2, the result of Equation (2.3-5) is

$$<P^2(t)> = W_T^2 + C_2 V k_t^2 (W_s/W_b)^{\frac{1}{2}} (f_b/f_s)/(8\pi\zeta^2 f_s) \qquad (2.3\text{-}6)$$

The first term is the static load contribution, the second term is the mean-square dynamic load. Any consistent set of units may be used in Equation (2.3-6). The units of the constant C_n are $(\text{length})^{3-n}(\text{cycles})^{n-1}$. The units of force predicted by Equation (3.5-5) are the units of the tire stiffness. These results estimate the total mean-square dynamic pavement loading in terms of the vehicle weight, stiffness, damping and speed and the pavement surface roughness.

As an example of the use of Equation (2.3-6), consider the data in Table 2.3-1 for the "Test Vehicle No. 1" in the loaded condition. From Equation (2.1-4), the vehicle parameters are:

k_t = 16,000 lbf/in $\qquad W_s/W_b = 0.1462$

$f_b = \sqrt{k_s/m_s}\ /2\pi = 1.7$ Hz.

$f_s = \sqrt{(k_s+k_t)/m_s}\ /2\pi = 12.3$ Hz.

$\zeta = c_s/2\sqrt{k_s m_b} = 0.109$

Substituting these values into Equation (2.3-6) one obtains the estimate of mean-square dynamic loading as

$$<P^2(t)> - W_T^2 = 4.174 \cdot 10^7 C_2 V \quad \text{lbf}^2$$

where the length dimension is in inches.

Expressing lengths in feet and speed in miles per hour one obtains (multiplying by: 144·88/60)

$$\langle P^2(t)\rangle - W_T^2 = 8.816\cdot 10^9 C_2 \overline{V} \quad \text{lbf}^2$$

where C_2 has units of ft-cycle and $\overline{V}$ is the speed in miles per hour.

To continue the example, suppose that the pavement surface roughness has a PSR index of 3.0. Then, from Equation (2.2-4) one estimates $C_2 = 3.402\cdot 10^{-7}$ ft-cycle, and the estimated mean-square loading is

$$\langle P^2(t)\rangle - W_T^2 = 2999.2\overline{V} \quad \text{lbf}^2$$

For several vehicle speeds, the estimated loading is:

$\overline{V}$,mph:	20	30	40	50	60
Mean-Square Load, lbf^2	59,984	89,976	119,968	149,960	179,952
Root-Mean-Square Load, lbf:	245.	300.	346.	387.	424.

For the static tire load of 9382 lbf, it is seen that the rms dynamic loading is estimated to be on the order of 2.6 percent to 4.5 percent of the static load. These results are typical for the other vehicles described in Table 2.3-1. Since the dynamic loading is the forcing of the pavement slab, one would expect the pavement/subgrade system response, if it is linear, to be proportional to the loading. Since the dynamic loading is rather low (a few hundred pounds), one would expect the pavement vibration response to be rather low. This result is observed in the experimental data in Appendix VI.

3.0 VEHICLE/PAVEMENT INTERACTION

Based upon the assumption of a rigid pavement, the surface loading induced by a vehicle or tire/axle system has been developed in Section 2. It is now assumed that the pavement responds to the loading in a linearly elastic fashion (2-16). For a prescribed pavement loading two basic techniques may be utilized for estimating the pavement response. One technique involves idealizing the pavement/subgrade system as a layered elastic half-space and is exceedingly complex from a mathematical standpoint (3-1). A much simplier and approximate technique is to idealize the pavement/subgrade response by a lumped parameter system. The lumped parameter approach has been shown to model pavement response to moving wheel loads (2-5, -16) and has been extensively applied in studying the motion of foundations and bases to oscillating loads (3-2, -3, -4).

To establish a basis for selecting a lumped parameter model of the pavement/subgrade system, a few relevant conclusions from the analysis of an elastic half-space subjected to moving loads will be mentioned. For a constant amplitude loading distributed over a circular area and moving with a constant velocity, it has been determined (3-5) that a point load is a good approximation to the distributed loading for estimating surface motion response at locations greater than three diameters from the distributed loading. The velocity dependent contribution to the surface motion response is on the order of a few percent of the total surface motion so that static loading response is a good approximation to the moving load problem.

For moving loads that simultaneously fluctuate during uniform motion across an elastic half space (3-6), a resonance phenomenon will exist if the speed of the moving load approaches that of free surface waves (e.g., Rayleigh Waves). Since normal traffic speeds are much lower than propagation speeds for surface waves, one cannot expect a resonance to result only from the translation of the moving load.

From the above observations it is concluded that for a load traversing a paved surface, such as that representing a highway/subgrade system, at a speed typical of highway traffic, the loading can be accurately approximated as a point load. Additionally, the velocity dependent displacements can be neglected in comparison to the total instantaneous loading comprised of the static component (vehicle weight) and the fluctuating loading resulting from the vehicle dynamic response to surface irregularities.

Hence, the lumped parameter model of a pavement/subgrade system being forced by a point impulse or oscillating load seems appropriate for the purposes of estimating ground motion response at a location adjacent to the highway. In using this model, it must be kept in mind that the analysis assumes that the observer is moving with the load along the highway. Hence, it is implicitly assumed that the pavement/subgrade mass and stiffness parameters are constant along the length of highway concerned. The nature of the traffic-induced vibration problem is such that vibration levels generally great enough to cause problems are confined to within a few hundred feet of the highway so that one can reasonably assume that the pavement/subgrade parameters are uniformly distributed. This assumption is consistent with that employed by highway design engineers for static considerations (2-1).

3.1 PAVEMENT/SUBGRADE LUMPED PARAMETER MODEL

In utilizing a lumped parameter model for the pavement/subgrade system, it must be remembered that traffic-induced vibration is an off-highway problem so that one need not be concerned with extreme detail of the deformation at the load for either the pavement or the subgrade but rather with the motion of the pavement/subgrade as related to prediction of the ground motion away from the highway.

The lumped parameter model of the pavement/subgrade system should include the effects of both the pavement and the subgrade mass and stiffness. In particular, to determine the appropriate mass and stiffness characteristics of the subgrade, the effective mass and radiation damping associated with outwardly propagating waves in the elastic subgrade should be considered. Many references (3-2, -3, -4) present appropriate lumping of the soil parameters for modeling the response of rigid masses resting on an elastic medium. This approach allows consideration of subgrade parameters, but ignores the stiffness of the pavement. Alternately, the pavement may be taken as an elastic plate resting on a massless Winker foundation (2-1, -5, 3-7) which allows consideration only of the subgrade stiffness. (See Reference 2-5, pp. 219-224, for a critical discussion of the use of a Winkler foundation model for subgrades).

By taking the pavement as an infinitely long elastic plate of finite width, it is possible to develop a lumped parameter model that considers both mass and stiffness effects of the pavement and the subgrade. This model has been analyzed by Dowell (3-8) and Vlasov and Leont'ev (3-9). The results of the variational method used by Dowell (3-8) are discussed in relation to developing an appropriate model of the pavement/subgrade system.

3.1.1 Equations of Motion

The model considered in the derivation is that of an elastic slab resting on an elastic subgrade. It is assumed that a plane stress condition can be approximated so that the model is representative of a transverse section of the pavement/subgrade system. The pavement or slab is assumed to be modeled as an elastic plate of thickness, h, width, 2a, and infinite length. The slab rests on an elastic subgrade of depth, H, that is of infinite extent.

The slab is assumed to be perfectly bonded to the subgrade and the subgrade is assumed to be perfectly bonded to a rigid subgrade as indicated in Figure 3.1-1. Hence the model is that of an elastic slab resting on a single layer subgrade. The objective of the analysis is to develop an appropriate lumping of the slab and subgrade parameters to approximate the frequency response of the system. The analysis presented here is adaptation of Dowell's analysis (3-8) to the highway vibration problem.

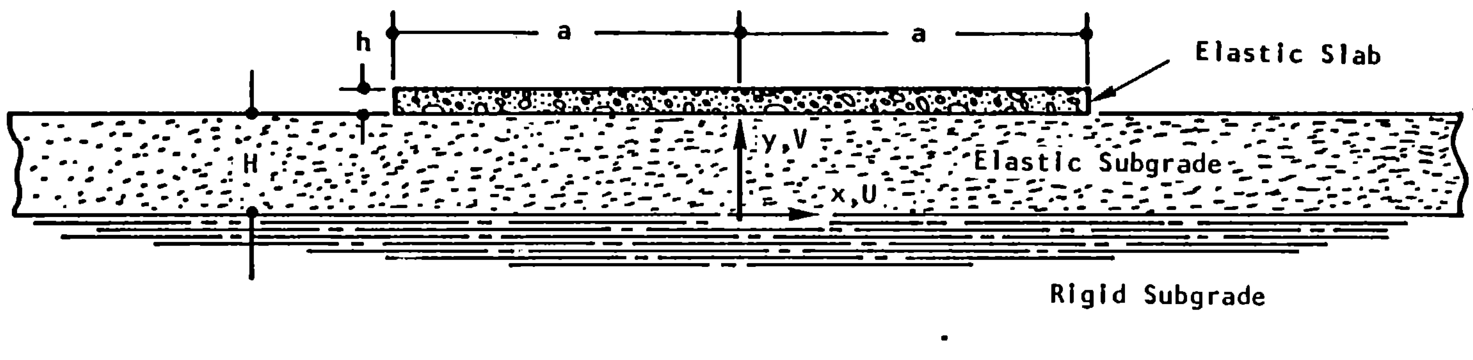


FIGURE 3.1-1 PAVEMENT/SUBGRADE LUMPED PARAMETER MODEL

For plane stress or plane strain, the Principle of Virtual Work is taken as

$$\delta W - \delta U = 0 \tag{3.1-1}$$

where $\delta W \equiv \int\int q\delta v dxdy + \int\int p\delta u dxdy$

$$\delta U \equiv \int\int (\sigma_{xx}\,\delta\varepsilon_{xx} + \sigma_{yy}\,\delta\varepsilon_{yy} + 2\sigma_{xy}\,\delta\varepsilon_{xy})\, dxdy$$

The term δW is the virtual work due to the body force components p and q and the term δU is the strain energy.

For plane stress, the strain-displacement relations and the stress-strain relations are given as

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} = u_{,x}\ ;\ \varepsilon_{yy} = \frac{\partial v}{\partial y} = v_{,y}\ ;\ \varepsilon_{xy} = u_{,y} + v_{,x}$$

$$\sigma_{xx} = \frac{E_f}{(1-\nu_f^2)}(\varepsilon_{xx} + \nu\varepsilon_{yy});\ \sigma_{yy} = \frac{E_f}{(1-\nu_f^2)}(\nu\varepsilon_{xx} + \varepsilon_{yy});\ \sigma_{xy} = \frac{E_f}{2(1+\nu_f)}\varepsilon_{xy} \tag{3.1-2}$$

It is seen from Equations (3.1-2) that the subgrade material is assumed to be homogeneous and isotropic with the elastic constants expressed in terms of Young's modulus, E, and Poisson's ratio, ν. The subscript f denotes the subgrade or foundation material.

The subgrade displacements, u(x,y,t) and v(x,y,t), are assumed to be of the form

$$u(x,y,t) = \Phi(y)\cdot U(x,t)$$
$$v(x,y,t) = \phi(y)\cdot V(x,t) \tag{3.1-3}$$

where the coordinates are defined in Figure 3.1-1.

The functions $\Phi(y)$ and $\phi(y)$ are selected to satisfy the boundary conditions

$$\Phi(y{=}0) = 0 \qquad \phi(y{=}0) = 0$$
$$\Phi(y{=}H) = 0 \qquad \phi(y{=}H) = 1 \tag{3.1-4}$$

Substituting the assumed subgrade displacements given by Equation (3.1-3) into the strain-displacement relations given by Equation (3.1-2) and performing the operations indicated in Equation (3.1-1), the equations of motion of the subgrade are obtained in the form

$$E_f^* \cdot \int \phi^2 \, dy \, \frac{\partial^2 U}{\partial x^2} - G_f \cdot \int (\phi')^2 \, dy \cdot U - \frac{1}{2} E_f^* \cdot (1 + \nu_f) \int \phi' \phi \, dy \cdot \frac{\partial V}{\partial x}$$

$$+ \int p \cdot \phi dy = 0 \qquad (3.1\text{-}5a)$$

$$G_f \cdot \int \phi^2 dy \cdot \frac{\partial^2 V}{\partial x^2} - E_f^* \int (\phi')^2 \, dy \cdot V + \frac{1}{2} E_f^* \, (1 + \nu_f) \int \phi' \phi \, dy \cdot \frac{\partial U}{\partial x}$$

$$+ \int q \cdot \phi dy = 0 \qquad (3.1.5b)$$

where $E_f^* = E_f/(1-\nu_f^2)$

$G_f = E_f/2(1+\nu_f)$

$\phi' = \frac{d\phi}{dy}$, etc.

The boundary conditions on $U(x,t)$ and $V(x,t)$ are, for x = constant:

$$E_f^* \left\{ \int \phi^2 \, dy \frac{\partial U}{\partial x} + \nu_f \int \phi \, \phi' \, dy \cdot V \right\} \equiv 0 \quad \text{or} \quad U \equiv 0 \qquad (3.1\text{-}6a)$$

$$G_f \left\{ \int \phi' \phi \, dy \cdot U + \int \phi^2 \, dy \cdot \frac{\partial V}{\partial x} \right\} \equiv 0 \quad \text{or} \quad V \equiv 0 \qquad (3.1\text{-}6b)$$

It is now assumed that the elastic subgrade depth, H, is less than the slab width, 2a, so that $H/2a < 1.0$. With this assumption, the slab/subgrade motion will be predominately transverse so that one can assume that $U \equiv 0$.

Assuming that the subgrade is loaded only through the region of contact with the slab one obtains including the effect of subgrade inertia

$$q(x,y,t) = q_s(x,t) \, \delta(y-H) - \rho_f \ddot{v}(x,y,t) \qquad (3.1\text{-}7a)$$

$$= q_s(x,t) \delta \, (y-H) - \rho_f \, \phi(y) \, \ddot{V}(x,t) \qquad (3.1\text{-}7b)$$

where $\delta(y-H)$ is the Dirac delta function and the over dots denotes a time derivative.

With those assumptions, the equation of motion of the subgrade becomes

$$m_f\ddot{V} - 2t_f V'' + k_f V = q_s(x,t) \tag{3.1-8}$$

where

$$m_f = \rho_f \int \phi^2 dy;\; k_f = E_f^* \int (\phi')^2 dy;\; t_f = \frac{1}{2} G_f \int \phi^2 dy$$

$$(\dot{\ }) = \frac{\partial (\ )}{\partial t}, \quad (\ )' = \frac{\partial (\ )}{\partial x}, \text{ etc.}$$

Now, the subgrade loading, q_s, is evaluated in terms of the response of the loaded slab. The slab/subgrade free-body diagram is illustrated in Figure 3.1-2. The equation of motion of the slab model subjected to trasverse loading $p_s(x,t)$ is taken as the case of bending of an infinitely long thin isotropic plate (3-10) and is given by

$$\begin{aligned} DV'''' = {} & p_s(x,t) - m_p\ddot{V} - q_s(x,t) \\ & -Q_f\big|_{x=+a}\delta(x-a) - Q_f\big|_{x=-a}\delta(x+a) \end{aligned} \tag{3.1-9}$$

where $D = E_p h^3/12(1-\nu_p^2)$, slab bending rigidity

m_p = mass per unit area of the slab = $\rho_p h$

$Q_f\big|_{x=\bar{x}}$ is the slab edge shear at $x=\bar{x}$

The edge shear forces applied to the slab as a result of requiring the slab to remain in contact with the subgrade are given by

$$Q_f\big|_{x=+a} = 2t_f[V'\big|_{x=+a^-} - V'\big|_{x=+a^+}] \tag{3.1-10a}$$

$$Q_f\big|_{x=-a} = 2t_f[V'\big|_{x=-a^-} - V'\big|_{x=-a^+}] \tag{3.1-10b}$$

where $V'\big|_{x=\pm a^+} = \lim\limits_{x\to\pm a^+} \left(\frac{dV}{dx}\right)$, " x approaches $\pm a$ from the right "

$V'\big|_{x=\pm a^-} = \lim\limits_{x\to\pm a^-} \left(\frac{dV}{dx}\right)$, " x approaches $\pm a$ from the left "

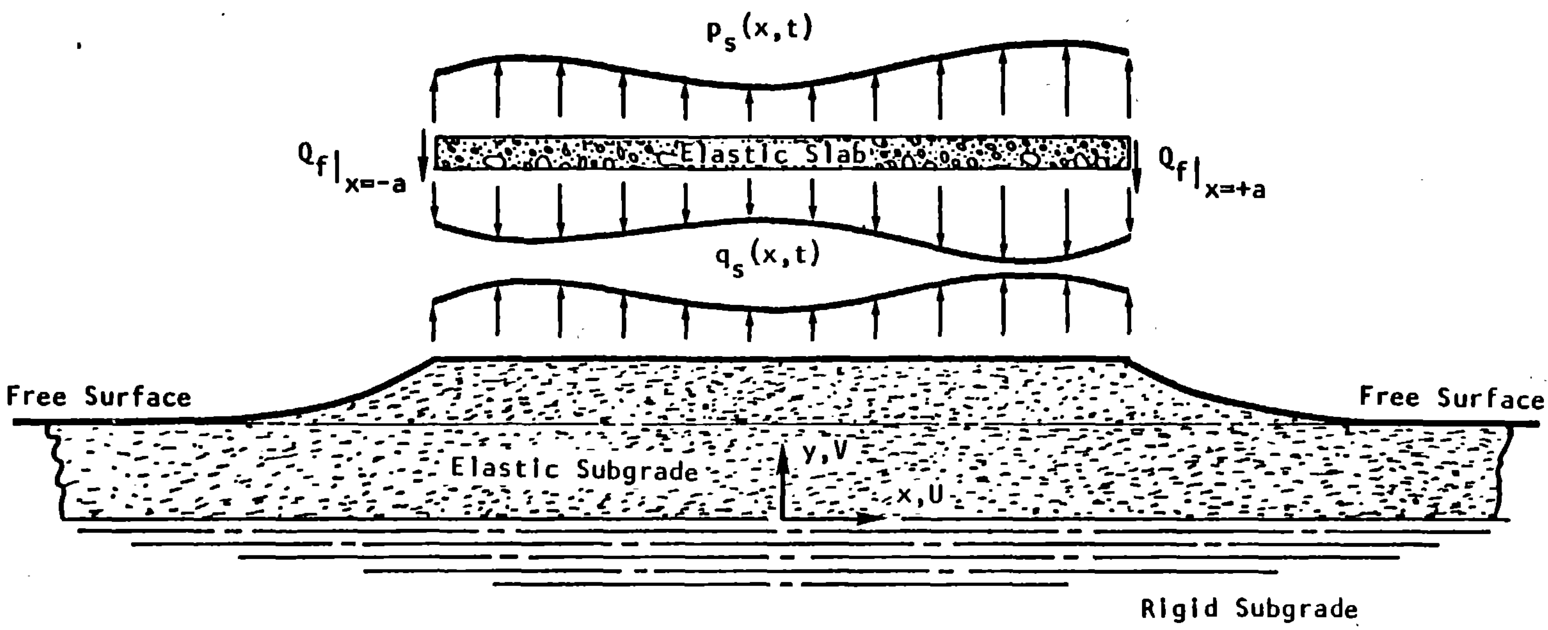


FIGURE 3.1-2 PAVEMENT/SUBGRADE FREE-BODY DIAGRAM

It is noted that $V(x,t)$ must be continuous for all x but that dV/dx is discontinuous at $x=\pm a$ as a result of $Q_f \neq 0$. The effect of the subgrade beyond the slab is determined by the terms $V'|_{x=+a^-}$ and $V'|_{x=-a^+}$.

From the work of Dowell (3-8), it is shown that the displacement function beyond the slab ($x<-a$ or $x>+a$) can be evaluated at $x = \pm a$ and that the derivatives $V'|_{x=+a^+}$ and $V'|_{x=-a^-}$ can be evaluated in terms of $V(x=\pm a,t)$ and $\dot{V}(x=\pm a,t)$ so that the slab edge shears are expressed as

$$Q_f|_{x=+a} = 2t_f[+V'(x=+a,t)+\sqrt{\frac{k_f}{2t_f}}\{\frac{\dot{V}(x=+a,t)}{\sqrt{(k_f/m_f)}} + V(x=+a,t)\}] \qquad (3.1\text{-}11a)$$

$$Q_f|_{x=-a} = 2t_f[-V'(x=-a,t)+\sqrt{\frac{k_f}{2t_f}}\{\frac{\dot{V}(x=-a,t)}{\sqrt{(k_f/m_f)}} + V(x=-a,t)\}] \qquad (3.1\text{-}11b)$$

It is noted that the $\dot{V}(x=\pm a,t)$ term represents the radiation damping of the slab/subgrade motion resulting from waves propagating away from the vibrating slab.

Noting that the surface loading of the plate by the subgrade reaction is given by $q_s(x,t)$ in Equation(3.1-8), the governing equation of motion of the slab is given by

$$DV'''' - 2t_fV'' + k_fV + (m_p + m_f)\ddot{V} = p_s(x,t) - Q_f|_{x=+a}\delta(x-a) - Q_f|_{x=-a}\delta(x+a) \qquad (3.1\text{-}12)$$

Equation (3.1-12) is the governing equation of motion for an elastic slab vibrating in contact with an elastic subgrade.

3.1.2 Solutions to the Equations of Motion

The solution to the equation of motion (3.1-12) is approximated using the Rayleigh-Ritz method (3-11) by assuming a deformation of the form

$$V(x,t) = \sum_{n=1}^{N} \Psi_n(x) a_n(t) \qquad -a \leq x \leq a \tag{3.1-13}$$

$\Psi_n(x)$ is an assumed slab mode

$a_n(t)$ is an unknown function of time

The solution procedure is to substitute the assumed displacement function $V(x,t)$ given by Equation (3.1-13) into the governing Equation (3.1-12), multiply by $\Psi_r(x)$ and integrate over the slab length $-a \leq x \leq a$ to obtain the N governing equations (r=1,2,...,N):

$$(m_p + m_f) \sum_n M_{nr} \ddot{a}_n(t) + 2t_f \beta \sum_n \Psi_{nr} \dot{a}_n(t)$$
$$+ \sum_n \{ DK_{nr} - 2t_f F_{nr} \} a_n(t) = \int_{-a}^{a} p_s(x,t) \Psi_r(x) \, dx \tag{3.1-14}$$

where $M_{nr} = \int_{-a}^{a} \Psi_n(x) \Psi_r(x) \, dx$

$$K_{nr} = \int_{-a}^{a} \Psi_n'''(x) \Psi_r(x) \, dx = [\Psi_n'''(x) \Psi_r(x) - \Psi_n''(x) \Psi_r'(x)] \Big|_{-a}^{a} + \int_{-a}^{a} \Psi_n''(x) \Psi_r''(x) dx$$

$$\Psi_{nr} = \Psi_n(a)\Psi_r(a) + \Psi_n(-a)\Psi_r(-a)$$

$$F_{nr} = -\alpha\{\Psi_{nr} + \alpha M_{nr} + \frac{1}{\alpha} \int_{-a}^{a} \Psi_n'(x)\Psi_r'(x) dx\}$$

$$\alpha = (k_f/2t_f)^{\frac{1}{2}} \qquad \beta = (m_f/2t_f)^{\frac{1}{2}}$$

To obtain the system of governing equations of motion in terms of the unknown generalized coordinates, $a_n(t)$, one only needs to select the functions $\phi(y)$ (See Equation (3.1-3)) and $\Psi_n(x)$ (see Equation (3.1-13)) to compute the coefficients in Equation (3.1-14). The only restriction is that $\phi(0) = 0$ and $\phi(H) = 1$. Otherwise, only engineering judgement guides the selection of $\phi(y)$ and $\Psi_n(x)$.

For instance, a good choice of functions for a four-term approximation (N=4) is

$\phi(y) = y/H$ linear subgrade extension

$\Psi_1(x) = 1.0$ rigid body slab translation

$\Psi_2(x) = \sqrt{3}x/a$ rigid body slab rotation

$\Psi_3(x)$ taken as the first symmetric free-free beam bending mode

$\Psi_4(x)$ taken as the first antisymmetric free-free beam bending mode.

Here, we select $\Psi_n(x)$ so that the mode shapes are normalized as

$$\int_{-a}^{a} \Psi_n(x)\, \Psi_r(x)\, dx = \begin{cases} 2a & n=r \\ 0 & n \neq r \end{cases}$$

Numerical data for these assumed modes are presented in Table 3.1-1 (See References 3-11, -12). The slab/subgrade motion for each of the assumed modes is illustrated in Figure 3.1-3.

Substituting the numerical results of Table 3.1-1 into the equations of motion given by Equation (3.1-14), one obtains the governing equations for $a_n(t)$, in matrix form, as

$$\begin{bmatrix} m_{ii} & 0 \\ 0 & m_{jj} \end{bmatrix} \cdot \begin{Bmatrix} \ddot{a}_i \\ \ddot{a}_j \end{Bmatrix} + \begin{bmatrix} c_{ii} & c_{ij} \\ c_{ij} & c_{jj} \end{bmatrix} \cdot \begin{Bmatrix} \dot{a}_i \\ \dot{a}_j \end{Bmatrix} + \begin{bmatrix} k_{ii} & k_{ij} \\ k_{ij} & k_{ij} \end{bmatrix} \cdot \begin{Bmatrix} a_i \\ a_j \end{Bmatrix} = \begin{Bmatrix} P_i(t) \\ P_j(t) \end{Bmatrix} \qquad (3.1\text{-}15)$$

Table 3.1-1

NUMERICAL DATA FOR ASSUMED SLAB MODES

Values of integrals appearing in Equation (3.1-14)

$$\int_{-a}^{a} \Psi_n(x)\Psi_r(x)dx = \begin{cases} 2a & n = r \\ 0 & n \neq r \end{cases}$$

$$\int_{-a}^{a} (\Psi_1'(x))^2 dx = 0 \qquad \int_{-a}^{a} (\Psi_3'(x))^2 dx = 24.74041/a$$

$$\int_{-a}^{a} (\Psi_2'(x))^2 dx = 6/a \qquad \int_{-a}^{a} (\Psi_4'(x))^2 dx = 54.46230/a$$

$$\int_{-a}^{a} (\Psi_1''(x))^2 dx = 0 \qquad \int_{-a}^{a} (\Psi_2''(x))^2 dx = 0$$

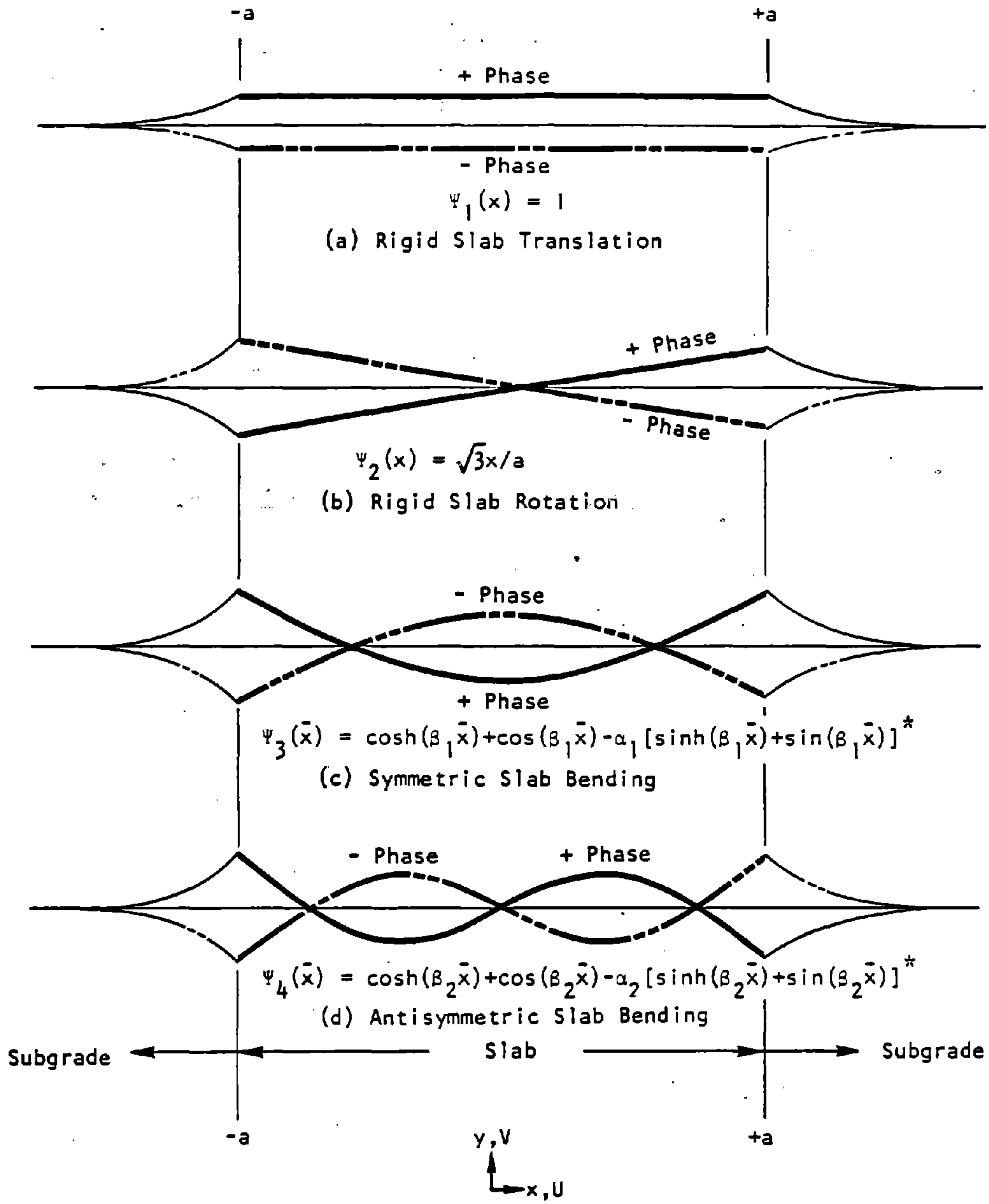
$$\int_{-a}^{a} (\Psi_3''(x))^2 dx = 62.57049/a^3$$

$$\int_{-a}^{a} (\Psi_4''(x))^2 dx = 475.44213/a^3$$

$$\int_{-a}^{a} \Psi_n'(x)\Psi_r'(x)dx = 0 \qquad \int_{-a}^{a} \Psi_n''(x)\Psi_r''(x)dx = 0 \qquad n \neq r$$

Values of $\Psi_n(x)$, $\Psi_n'(x)$, $\Psi_n''(x)$, and $\Psi_n'''(x)$ for $x = \pm a$

$\Psi_1(a) = 1$	$\Psi_1'(a) = 0$	$\Psi_1''(a) = 0$	$\Psi_1'''(a) = 0$
$\Psi_1(-a) = 1$	$\Psi'_1(-a) = 0$	$\Psi_1''(-a) = 0$	$\Psi_1'''(-a) = 0$
$\Psi_2(a) = \sqrt{3}$	$\Psi_2'(a) = \sqrt{3}/a$	$\Psi_2''(a) = 0$	$\Psi_2'''(a) = 0$
$\Psi_2(-a) = -\sqrt{3}$	$\Psi_2'(-a) = \sqrt{3}/a$	$\Psi_2''(-a) = 0$	$\Psi_2'''(-a) = 0$
$\Psi_3(a) = 2.0000$	$\Psi_3'(a) = 1.9650$	$\Psi_3''(a) = 0.0000$	$\Psi_3'''(a) = 0.0000$
$\Psi_3(-a) = 2.0000$	$\Psi_3'(-a) = -1.9650$	$\Psi_3''(-a) = 0.0000$	$\Psi_3'''(-a) = 0.0000$
$\Psi_4(a) = 2.0000$	$\Psi_4'(a) = -2.0016$	$\Psi_4''(a) = 0.0000$	$\Psi_4'''(a) = 0.0000$
$\Psi_4(-a) = 2.0000$	$\Psi_4'(-a) = -2.0016$	$\Psi_4''(-a) = 0.0000$	$\Psi_4'''(-a) = 0.0000$



* $\bar{x} = x+a$; $2\beta_1 a = 4.73004$; $2\beta_2 a = 7.85320$; $\alpha_1 = 0.98250$; $\alpha_2 = 1.00078$

FIGURE 3.1-3 ASSUMED PAVEMENT/SUBGRADE VIBRATION MODES where

$$j = i+2 \qquad i = 1,2$$

$$m_{11} = m_{22} = m_{33} = m_{44} = (1 + \mu) \qquad \mu = m_p/m_f$$

$$c_{11} = \varepsilon\omega_f \quad c_{13} = 2\varepsilon\omega_f \quad c_{33} = 4\varepsilon\omega_f$$

$$c_{22} = 3\varepsilon\omega_f \quad c_{24} = -2\sqrt{3}\,\varepsilon\omega_f \quad c_{44} = 4\varepsilon\omega_f$$

$$k_{11} = (1+\varepsilon)\,\omega_f^2 \quad k_{13} = 2\varepsilon\omega_f^2$$

$$k_{33} = [31.295\ (D/k_f a^4) + 1+4\varepsilon + 12.37\varepsilon^2]\,\omega_f^2$$

$$k_{22} = (1+3\varepsilon+3\varepsilon^2)\,\omega_f^2 \qquad k_{24} = -2\sqrt{3}\,\varepsilon\omega_f^2$$

$$k_{44} = [237.721\ (D/k_f a^4) + 1+4\varepsilon + 27.231\varepsilon^2]\,\omega_f^2$$

$$P_1(t) = \frac{\omega_f^2}{2k_f a}\int_{-a}^{a} p_s(x,t)\,dx \qquad P_2(t) = \frac{\sqrt{3}\,\omega_f^2}{2k_f a}\int_{-a}^{a} p_s(x,t)(x/a)\,dx$$

$$P_3(t) = \frac{\omega_f^2}{2k_f a}\int_{-a}^{a} p_s(x,t)\Psi_3(x)\,dx \qquad P_4(t) = \frac{\omega_f^2}{2k_f a}\int_{-a}^{a} p_s(x,t)\Psi_4(x)\,dx$$

$$m_f = \rho_f H/3 \qquad \mu = m_p/m_f \qquad \omega_f^2 = k_f/m_f$$

$$\varepsilon = (2t_f/k_f)^{\frac{1}{2}}/a \qquad k_f = E_f/H(1-\nu_f^2) \qquad t_f = HE_f/12(1+\nu_f) = HG_f/6$$

$$\varepsilon = \sqrt{(1-\nu_f)/6}\cdot(H/a)$$

$D/k_f = \ell^4$ (ℓ is the radius of relative stiffness of the slab)

As seen in Equation (3.1-15), the symmetric modes couple and the antisymmetric modes couple with the coupling term dependent upon the magnitude of the parameter ε. Typical values of ε are between 0.2 and 0.5 for the assumed restriction $H/2a<1$.

The effort to this point has been to derive a lumped parameter model of an elastic slab vibrating in contact with an elastic subgrade. The objective of this effort was to determine the relationships between elastic and mass parameters for the slab and the subgrade and to determine the frequency response functions for the slab motion. The coefficients in Equation (3.1-15) indicate the appropriate grouping of slab and subgrade parameters. In particular, the parameter k_f is the Winkler foundation stiffness commonly called the modulus of subgrade reaction in highway design. The ratio of the slab bending rigidity, D, to the stiffness k_f is the radius of relative stiffness of the slab raised to the fourth power. The coupling parameter, ε, is the ratio of extensional stiffness, k_f, to the shear stiffness, t_f, of the subgrade and indicates the significance of subgrade shearing rigidity or alternately the significance of subgrade depth. All of these parameters, two of which are common highway design parameters, were derived quite independently from basic considerations. Hence, the present analysis relates directly to design parameters used in practical highway engineering.

3.1.2.1 Pavement/Subgrade Uncoupled Motion

As indicated by Equations (3.1-15) the symmetric slab/subgrade modes are coupled and the antisymmetric modes are coupled. The solution procedure for Equations (3.1-15) is to determine the roots of the eigenvalue problem obtained by setting the right hand side of Equations (3.1-15) to zero (i.e., assuming free motion) and substituting $a_i(t)=A_i e^{\lambda t}$. With the coupled equations, the determination of λ involves the solution of a general 4th order polynomial in λ - not an easy task without a computer. As for the coupled vehicle motion (see Section 2.1), it is desirable to see if the slab/subgrade natural frequencies can be approximated by neglecting the coupling terms c_{ij} and k_{ij} in Equation (3.1-15). A numerical study was conducted using typical slab/subgrade parameters and variations of the slab depth, H, to determine the degree of approximation involved in ignoring the coupling terms. As a result, it appears reasonable to do so since the approximate natural frequencies always agreed with the coupled natural frequencies within a few percent.

Hence, ignoring the coupling terms, the equations for uncoupled motion become (from Equation 3.1-15)

$$\ddot{a}_1+2\zeta\omega_1\dot{a}_1+\omega_1^2 a_1 = K\int_{-a}^{a} p_s(x,t)dx \qquad (3.1\text{-}16a)$$

$$\ddot{a}_3+8\zeta\omega_1\dot{a}_3+\omega_3^2 a_3 = K\int_{-a}^{a} p_s(x,t)\Psi_3(x)dx \qquad (3.1\text{-}16b)$$

$$\ddot{a}_2+6\zeta\omega_1\dot{a}_2+\omega_2^2 a_2 = K\int_{-a}^{a} p_s(x,t)\Psi_2(x)dx \qquad (3.1\text{-}16c)$$

$$\ddot{a}_4+8\zeta\omega_1\dot{a}_4+\omega_4^2 a_4 = K\int_{-a}^{a} p_s(x,t)\Psi_4(x)dx \qquad (3.1\text{-}16d)$$

where $\zeta = \varepsilon/\varepsilon_c \quad \varepsilon_c=2\sqrt{\kappa_1 m} = 2\sqrt{(1+\varepsilon)(1+\mu)}$

$$\omega_i^2 = (\kappa_i/m)\omega_f^2 \; ; \; \omega_f^2 = k_f/m_f = 3E_f/\rho_f H^2(1-\nu_f^2)$$

$$m = 1+\mu \; ; \; K = 1/2a(m_p+m_f)$$

$$\kappa_1 = 1+\varepsilon$$

$\kappa_2 = 1+3\varepsilon+3\varepsilon^2$

$\kappa_3 = 1+4\varepsilon+12.37\varepsilon^2+31.295(\ell/a)^4$

$\kappa_4 = 1+4\varepsilon+27.231\varepsilon^2+237.721(\ell/a)^4$

Equation (3.1-16a) is for rigid slab translation, (3.1-16b) is for symmetric slab bending, (3.1-16c) is for rigid slab rotation, and (3.1-16d) is for antisymmetric slab bending.

The uncoupled damped natural frequencies associated with each slab motion given in Equations (3.1-16) are the imaginary parts of the following expressions:

(a) Rigid Slab Translation

$$\lambda_{1,2} = -\omega_f\omega_1[\zeta\pm i\sqrt{1-\zeta^2}\,] \tag{3.1-17a}$$

(b) Symmetric Slab Bending

$$\lambda_{1,2} = -4\omega_f\omega_1[\zeta\pm i\sqrt{(\kappa_3/4\kappa_1)^2-\zeta^2}] \tag{3.1-17b}$$

(c) Rigid Slab Rotation

$$\lambda_{1,2} = -3\omega_f\omega_1[\zeta\pm i\sqrt{(\kappa_2/3\kappa_1)^2-\zeta^2}] \tag{3.1-17c}$$

(d) Antisymmetric Slab Bending

$$\lambda_{1,2} = -4\omega_f\omega_1[\zeta\pm i\sqrt{(\kappa_4/4\kappa_1)^2-\zeta^2}] \tag{3.1-17d}$$

3.1.2.2 Pavement/Subgrade Frequency Response Functions

The uncoupled frequency response functions for the slab/subgrade system are obtained from Equations (3.1-16) by taking the slab loading as a point load of magnitude P_o located at $-a\leq x=d\leq a$ and assuming a harmonic time variation. Then, the slab loading is expressed as

$$p_s(x,t) = P_o\delta(x-d)e^{i\omega t} \qquad -a\leq d\leq a \tag{3.1-18}$$

For harmonic forcing, the slab/subgrade response will also be harmonic so that

$$a_n(t) = Q_n e^{i\omega t} \qquad n = 1,2,3,4 \qquad (3.1\text{-}19)$$

Substituting these results into Equations (3.1-16) and introducing the dimensionless frequency parameter $r=\omega/\omega_o$ the frequency response functions become

(a) Rigid Slab Translation

$$Q_1 = \overline{P}/[q_1^2-r^2+i2\zeta q_1 r] \qquad (3.1\text{-}20a)$$

(b) Rigid Slab Rotation

$$Q_2 = \overline{P}(d/a)/[q_2^2-r^2+i6\zeta q_1 r] \qquad (3.1\text{-}20b)$$

(c) Symmetric Slab Bending

$$Q_3 = \overline{P}\Psi_3(d)/[q_3^2-r^2+i8\zeta q_1 r]$$

(d) Antisymmetric Slab Bending

$$Q_4 = \overline{P}\Psi_4(d)/[q_4^2-r^2+i8\zeta q_1 r] \qquad (3.1\text{-}20d)$$

where $q_i = \omega_i/\omega_o$

$\overline{P} = KP_o/\omega_o^2$

$K = 1/2a(m_p+m_f)$

ω_i is defined in Equation (3.1-16)

3.2 PAVEMENT/SUBGRADE RESPONSE TO LOADING

This section develops the relationships for estimating the pavement response to dynamic loading. The model described in Section 3.1 for the pavement/subgrade system is complicated in appearance, and when coupled with the vehicle forcing becomes even more complicated. Hence, a rational approximation is used to simplify the problem. First, the forcing excitation described in Section 2.3 is estimated to occur in the frequency range around 10 Hz. From Equations (3.1-16) and (3.1-17) it is seen that the estimated pavement/subgrade natural frequencies are well separated and that the damping for the higher modes (slab rotation and bending) are on the order of 3 to 4 times the fundamental mode (rigid slab translation). By evaluating the appropriate physical parameters using typical configurations of pavement/subgrade systems, it appears that the fundamental pavement/subgrade mode generally occurs in the frequency range above 25 Hz. Hence, one would expect that if the pavement/subgrade system vibrates as a result of vehicle loading that the response would be of the nature of a forced motion rather than a resonant response. That is, for normal configurations of pavement/subgrade systems, the pavement is "detuned" from the vehicle.

Further, the analysis of Section 3.1 assumes that the slab section is of "unit length". For a slab that is long compared to its width, it is appropriate to consider the slab to be rigid in the direction of its width, but it must be flexible along its length. It was beyond the scope of the present project to consider this aspect of the problem. As a further approximation, it was assumed that the longitudinal deflection of the slab would be approximated by the static deflection of a slab on an elastic foundation (Reference 3-10, page 267). As an approximation, it was assumed that an "effective length" of the slab would be a distance in the longitudinal direction such that the static deflection was 0.10 of the deflection under the load (20 dB down). This distance is approximately 2.75 ℓ where ℓ is the radius of relative stiffness (See Table 3.1-1). The assumed slab deflection in the transverse and the longitudinal directions are illustrated in Figure 3.2-1. Hence, the "effective length" is estimated to be $2(2.75\ell) = 5.5\ell$.

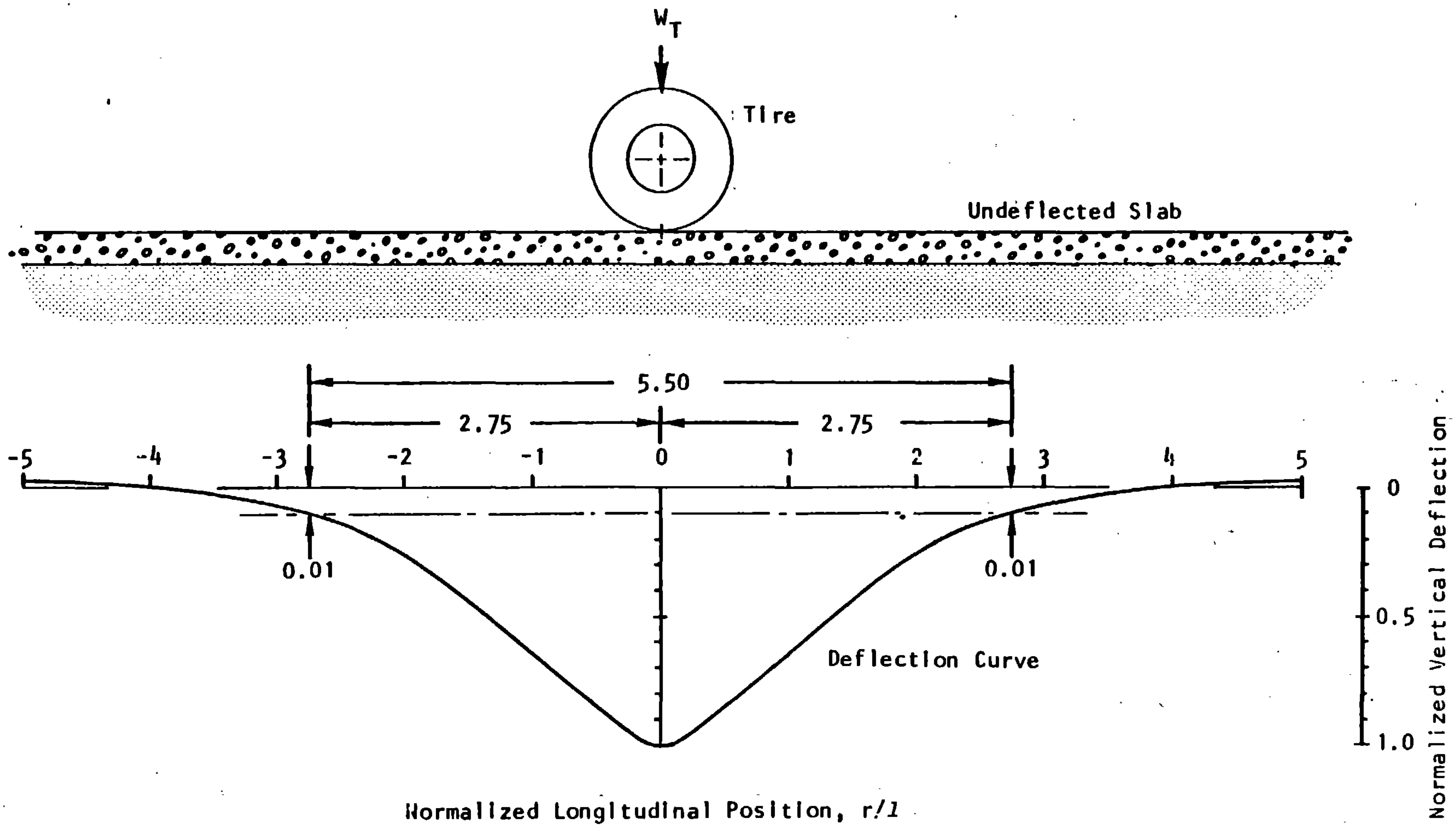


FIGURE 3.2-1. ASSUMED SLAB LONGITUDINAL DEFLECTION

Considering the slab to respond to the forcing only in the fundamental mode (rigid translation), the equation of motion for the slab becomes (See Equation (3.1-12)),

$$(m_p+m_f)b\ddot{V}_1(t) + 2\sqrt{2m_f t_f}\,\dot{V}_1(t) + \left[bk_f+2\sqrt{2k_f t_f}\right]V_1(t) = p(t)/5.5\ell \qquad (3.2\text{-}1)$$

where b is the slab width = 2a

$m_p = \rho_p h$ is the mass per unit area of the pavement

$m_f = \rho_f H/3$ is the mass per unit area of the subgrade

$k_f = E_f/H(1-\nu_f^2)$ is the modulus of subgrade reaction

$t_f = HE_f/12(1+\nu_f)$ is the subgrade shear stiffness

p(t) is the time dependent point-loading of the slab

5.5ℓ is the "effective length" see Figure 3.2-1

ℓ is the radius of relative stiffness.

Depending upon the nature of the loading, p(t), the equation of motion given by Equation (3.2-1) may be solved. For the problem of traffic-induced vibration, the response will be estimated for impact loading and for random loading.

First, it is convenient to divide Equation (3.2-1) by the mass term and to define the damping ratio, ζ_f, and the natural frequency, ω_f, for the assumed vibration mode of Figure 3.2-1. The equation of motion has the form:

$$\ddot{V}_1(t) + 2\zeta_f\omega_f\dot{V}_1(t) + \omega_f^2 V_1(t) = p(t)/M_f \qquad (3.2\text{-}2)$$

where $M_f = 5.5(m_p+m_f)b\ell$ "Effective Mass" of subgrade.

$K_f = k_f b + 2\sqrt{2k_f t_f}$ $\quad C_f = 2\sqrt{2m_f t_f}$

$\zeta_f = C_f/2\sqrt{b(m_p+m_f)K_f}$ $\quad \omega_f^2 = K_f/[b(m_p+m_f)]$.

All terms are defined by Equations (3.2-1) and (3.2-2).

3.2.1 Pavement/Subgrade Response to Impulsive Loading

To estimate the response of the pavement/subgrade system to an impact or impulse load, the results of Section 2.3.1 are used to estimate the maximum impulse load. This load is assumed to define a rectangular pulse of duration t' (the time for the tire to pass over the bump). The pulse time is the bump length divided by the vehicle speed.

The solution of Equation (3.2-2) for a rectangular pulse is described in any text book on differential equations. To conform with the requirements of the experimental program, maximum acceleration response is required. To simplify the problem, it will be assumed that the damping is zero. This will result in larger values for the pavement response than might be estimated including damping.

The maximum acceleration response of the pavement/subgrade is estimated to be:

$$\ddot{V}_1(t) = 2|P_{max}|/M_f \quad \text{for } o \leq t' \leq t \qquad (3.2\text{-}3a)$$

$$\ddot{V}_1(t) = 2|P_{max}| \cdot |SIN(\pi t'/T)|/M_f \quad \text{for } t' > t \qquad (3.2\text{-}3b)$$

Dividing both sides of this result by the constant acceleration due to gravity, g, and expressing the result as an acceleration level, one obtains:

$$L_{max} = 20\log(|P_{max}|) - 20\log(W_f) + 6 \text{ dB} \quad o \leq t' \leq t \qquad (3.2\text{-}4a)$$

$$L_{max} = 20\log(|P_{max}|) - 20\log(W_f) + 20\log(|SIN(\pi(f_f/f_s)/2v)|) + 6 \text{ dB} \quad t' > t \qquad (3.2\text{-}4b)$$

where P_{max} is given by Equations (2.3-1)

$f_f = \omega_f/2\pi$ is the pavement/subgrade frequency given by Equation (3.2-2)

$f_s = \omega_s/2\pi$ vehicle suspension frequency given by Equation (2.1.4)

v is the vehicle speed ratio given by Equation (2.3-1)

$W_f = {}_gM_f$ is the "effective" pavement/subgrade weight.

The result of Equation (3.2-4) is the estimate of the maximum acceleration level in dB (re. $1g_{peak}$) of the pavement response to the impulse load.

3.2.2 Pavement/Subgrade Response to Random Loading

In order to estimate the pavement response to random loading it is necessary to evaluate the frequency response function for the pavement/subgrade system. From Equation (3.2-2) one obtains

$$\overline{V}_1(\omega) = \overline{V}_1(\omega)\overline{P}/M_f \qquad (3.2\text{-}5)$$

where $\overline{V}_1(\omega) = [\omega_f^2-\omega^2+i2\zeta_f\omega_f\omega]^{-1}$

$\overline{P}$ is the amplitude of the dynamic loading at frequency ω

M_f is the "effective" subgrade mass

ω_f is the pavement/subgrade fundamental frequency.

As discussed in Section 2.3.2, the dynamic pavement loading is assumed to be predominately a forcing at the suspension system frequency ω_s. The power spectral density function of the pavement response, $S_v(\omega)$, is obtained from Equation (3.2-5) and Equation (2.3-4) as

$$S_v(\omega) = \overline{V}_1(\omega)\overline{V}_1{}^*(\omega)S_p(\omega)/M_f^2 \qquad (3.2\text{-}6)$$

where $\overline{V}_1{}^*(\omega)$ is the complex conjugate of $\overline{V}_1(\omega)$.

The mean-square pavement/subgrade displacement response to the random loading at the suspension system frequency is obtained by evaluating Equation (3.2-6) at $\omega=\omega_s$. The mean-square pavement/subgrade acceleration response to the random loading at the suspension system frequency is obtained by multiplying the displacement response by ω_s^4.

Doing this, one obtains the mean-square estimate of the pavement/subgrade acceleration response as:

$$S_v(\omega_s) = \omega_s^4\overline{V}_1(\omega_s)\overline{V}_1{*}(\omega_s)S_p(\omega_s)/M_f^2 \qquad (3.2\text{-}7)$$

From equation (3.1-5) and Equation (2.3-4) one obtains:

$$f_s^4\overline{V}_1(f_s)\overline{V}_1{*}(f_s) = [((f_f^2/f_s)^2-1)^2+4\zeta_f^2(f_f/f_s)^2]^{-1} \qquad (3.2\text{-}8a)$$

$$S_p(f_s) = C_nV^{n-1}k_t^2(W_b/W_s)^{(1-n)/2}(f_b/f_s)^{3-n}/(8\pi\zeta^2f_s{}^{n-1}) \qquad (3.2\text{-}8b)$$

where the results are expressed in terms of circular frequency in Hz.

The result given by Equation (3.2-8a) is the pavement/subgrade response to the random loading. Equation (3.2-8b) is the value of the excitation spectral density function at the suspension system natural frequency, $f_s = \omega_s/2\pi$, Hz. The pavement/subgrade response is just the product of these two terms divided by M_f^2. Dividing this product by the constant acceleration due to gravity, g, and expressing the result as a level in dB (re. 1 g_{rms}) one obtains:

$$L_1 = 10\log(S_p(f_s))-20\log(W_f) \qquad (3.2\text{-}9)$$

$$- 10\log[((f_s/f_f)^2-1)^2+4\zeta_f^2(f_f/f_s)^2] \text{ dB (re.1}g_{rms})$$

where $W_f = gM_f$ is the "effective" subgrade weight

$S_p(f_s)$ is given by Equation (3.2-8b).

The result of Equation (3.2-9) is the pavement/subgrade response acceleration level expressed in dB (re. $1g_{rms}$). This level is for one contact location of the tire(s) to the pavement system. For either dual tire systems or dual-tandem tire systems the value of the "tire stiffness" to use in Equation (3.2-8b) is the total tire stiffness for all tires carrying the weight W_T. In terms of the axle loading, the value of the total tire stiffness will double due to the two contact locations for the tires on either side of the axle. Similarly, the total weight carried by the axle is $2W_T$. Hence, the total mean-square axle load is obtained by multiplying Equation (2.3-6) by a factor of 2. The pavement/subgrade response acceleration level due to the dynamic axle load is simply the result of Equation (3.2-9) plus 6 dB.

Since the pavement/subgrade system was assumed to be rigid in the direction of its width, the results apply to any location across the slab width.

The result presented in Equation (3.2-9) is the traffic-induced vibration "source equation". It postulates a functional relationship between detail vehicle and pavement/subgrade parameters. Also, the estimate applies to a location on a rigid slab. Using typical data, the predictions resulting from the use of Equation (3.2-9) are very high (perhaps as much as 40 dB to 50 dB above typical acceleration levels measured at locations adjacent to the pavement). Hence, Equation (3.2-9) may be appropriate for pavement response but it does not account for "coupling losses" between the edge of the slab and the surrounding soil system. (See Figure 3.1-2, page 3-8). However, the functional form appears to be reasonable. As described in Appendix VI, many of the detail parameters in Equation (3.2-9) constitute the "site constants" and the regression coefficients determined during a "site calibration test". The "coupling losses" mentioned above also contribute to the "site constant". Hopefully, the result of Equation (3.2-9) will be useful in the formulation and reduction of field test data rather than an absolute prediction equation.

4.0 PROPAGATION OF GROUND MOTION FROM THE HIGHWAY

The analysis of Sections 2.0 and 3.0 provide the models for determining the loading and the response of the pavement/subgrade system to vehicles passing over discrete bumps and moving along highway surfaces that exhibit a random roughness. Now, the propagation of the surface waves from the highway source will be considered. The consideration here is to determine the decay or attenuation of highway traffic-induced vibration with distance. The attenuation model selected is based upon available experimental evidence (3-2), (3-3).

4.1 ATTENUATION MODEL: CONSTANT SOURCE-RECEIVER DISTANCE

Assuming cylindrical spreading of surface waves from the source (Rayleigh Surface Waves) and an exponential decay of amplitude due to absorption of the wave energy by the soil, the amplitude of surface motion at a distance, d, from the source (point of loading) is

$$W = EXP[-\eta(d-d_o)]\sqrt{d_o/d}\ W_o \qquad (4.1\text{-}1)$$

where W_o is the ampitude of the ground displacement at d_o (a convenient length $<d$)

W is the amplitude of the ground displacement at $d>d_o$

The above attenuation model assumes that the attenuation coefficient, η, is frequency independent. It is known that η generally exhibits a frequency dependence and a dependence upon Rayleigh Wave speed (i.e., $\eta=\eta^*\omega/v_r$). Such that higher frequency components attenuate more rapidly than lower frequency components and that subgrade materials that exhibit higher Rayleigh Wave propagation speeds (i.e., higher shear stiffness) attenuate surface wave motion less effectively (3-1), (3-2), (4-1).

The above result is used to evaluate the attenuation of surface waves with distance. The response quantity indicated in Equation (4.1-2) is the vertical displacement of the ground motion. One may use the same relationship for estimating velocity or acceleration as might be appropriate by replacing W_o by $\dot{W}_o$ or $\ddot{W}_o$.

For the above attenuation model, the term $\sqrt{d_o/d}$ is called the geometrical damping factor and the term $\exp[-\eta(d-d_o)]$ is called the absorption factor. The absorption damping, as taken here, is consistent with the model for radiation damping used to develop the pavement/subgrade response, Equation (3.1-10). Dowell's work (3-8) expresses the absoption damping factor, η, as an analytical result

$$\eta = [(k_f + m_f\omega^2)/2t_f]^{1/2} \qquad (4.1\text{-}2)$$

and from static considerations (i.e., ω=o) yields a scale length in terms of the subgrade depth

$$d_o = \sqrt{(1-\nu_f)/6} \cdot H = 2a\varepsilon \qquad (4.1\text{-}3)$$

The subgrade parameters k_f, m_f, and t_f are defined by Equation (3.1-8). However, it is probably more accurate to use available experimental data for the parameter, η.

With the receiver fixed at a point relative to the highway two considerations arise. First, if the vibration is caused by a discrete bump, the source is assumed to be located at the bump and the distance, d, in Equation (4.1-1) is constant. For a vehicle moving along a road surface characterized by a random roughness, the source-receiver distance varies with time so that with a constant mean-square value of the pavement/subgrade response (see Section 3.2.2) the amplitude of the ground motion at the receiver will increase as the vehicle approaches and decrease as the vehicle departs. This is totally analogus to the highway noise simulation models.

4.2 ATTENUATION MODEL: TIME-VARYING SOURCE-RECEIVER DISTANCE

For a time-varying source-receiver distance, $d(t)$ is determined in relation to the highway alignment relative to the receiver location. The vehicle, as a source, is assumed to move along the highway at a constant speed, V. Assuming that the vehicle speed is slow compared to the propagation speed of surface waves transmitted through the soil and that the pavement/subgrade response is independent of the vehicle position, the mean-square acceleration amplitude at the receiver is given by the expression

$$\ddot{W}^2(t) = d_o e^{-2\eta(d-d_o)} \overline{\ddot{w}_o^2(t)}/d(t) \tag{4.2-1}$$

where $\overline{\ddot{w}_o^2(t)}$ is the maximum mean-square value of the ground acceleration at a distance d_o from the source at a reference time, t=o

Assuming that the highway alignment is straight and that the receiver is located at a distance $\overline{d}$ from the highway, the distance $d(t)$ is expressed as

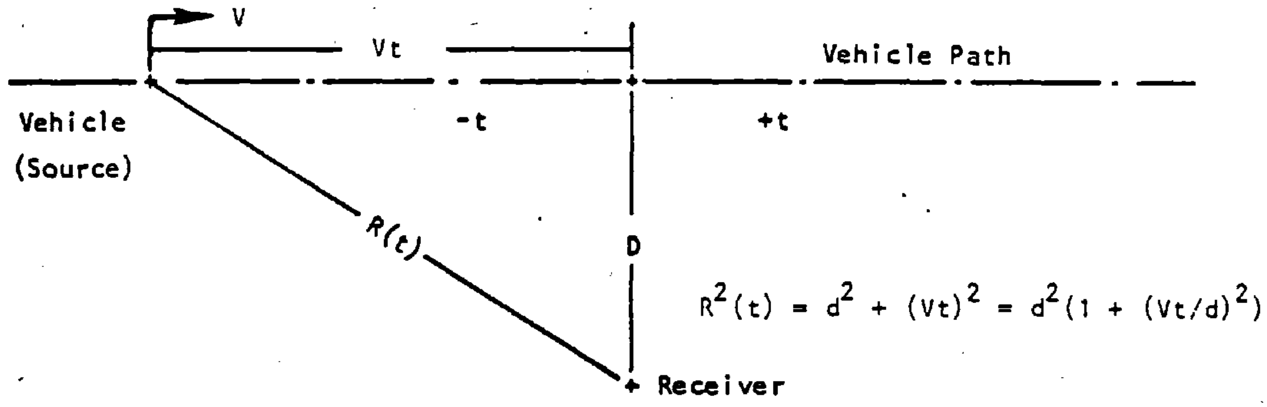
$$d(t) = \overline{d}[1+(Vt/\overline{d})^2]^{\frac{1}{2}} \tag{4.2-2}$$

where t is taken equal to zero when the source-receiver distance is $\overline{d}$.

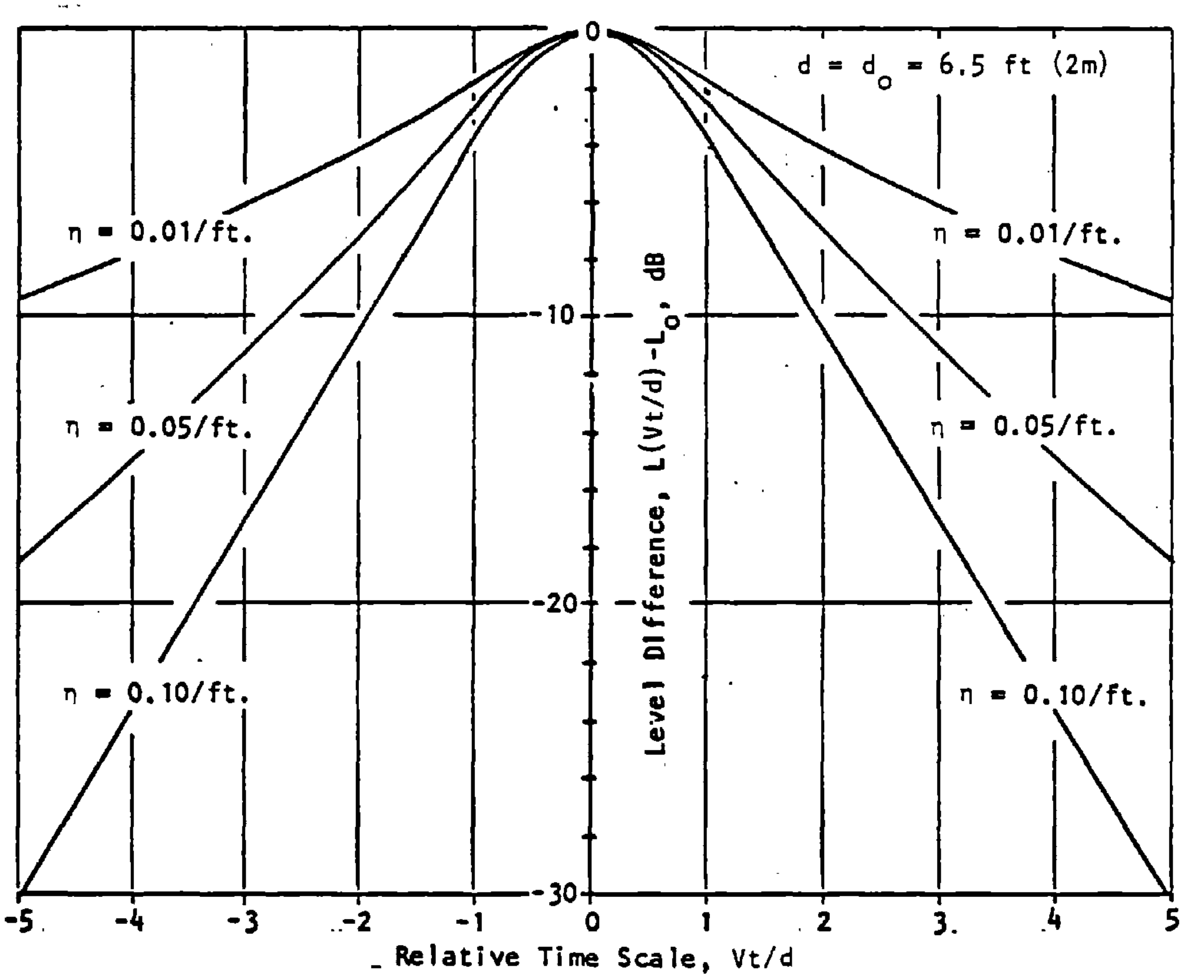
The source-receiver geometry from the time-varying distance, $d(t)$, modeled by Equation (4.2-1), is presented in Figure 4.2-1.

In using the result given in Equation (4.2-1), the expression for mean-square displacement or velocity can be substituted for mean-square acceleration as appropriate. The expressions for the mean-square pavement/subgrade response are given by Equation (3.2-9).

For a single vehicle pass-by the total vibration energy transmitted to the receiver is obtained by integrating Equation (4.2-1) over the duration or time period of the pass-by. The average vibration energy transmitted to



(a) Source-Receiver Geometry: Straight Segment



(b) Level Difference versus Relative Time Scale

FIGURE 4.2-1. SOURCE-RECEIVER GEOMETRY

the receiver is obtained. Due to the rapid distance attenuation of vibration and the difficulties in obtaining explicit functional forms for the integrations with finite limits, it will be assumed that an infinite integration time is allowable and a finite duration upon which to "average" the energy is allowable. Even with this assumption, the integrations are not obtained in terms of "convenient" functions. The techniques and approximations used to obtain the explicit integrations are described in Section 4.3.

Integrating the result of Equation (4.2-1) over an infinite time period (to simulate a single vehicle pass-by) one obtains the total vibration energy transmitted to the receiver. (Expressing this result in dB, one would obtain the "single-event" or equivalent vibration "shock" level for the single vehicle pass-by. This level metric is, perhaps, the most appropriate metric to use for the traffic-induced vibration problem. However, the development of a new metric and the associated formulation of the traffic flow model was beyond the scope of the present program.) Dividing the total vibration energy by the time period, T, for the pass-by and by g^2 (the reference acceleration level) and expressing the result in dB (re. $1g_{rms}$) one obtains:

$$L_e(\overline{d}) = L_o + 10\log(d_o/VT) - 20\log(e)\eta(\overline{d}-d_o) - 5\log(\eta\overline{d}) + 5\log(\pi) \qquad (4.2\text{-}3)$$

where: $L_o = 10\log(\overline{\ddot{w}_o^2(t)}/g^2)$ is the peak pass-by level at a distance d_o from the receiver. This level is expressed in dB (re. $1g_{rms}$).

It is noted that, other than the form of the distance attenuation term, Equation (4.2-3) is identical to the form to the equivalent sound level metric used in traffic flow noise analyses. By omitting the term (d_o/VT) from Equation (4.2-3) and defining the reference level as

$$L_o = 10\log(\ddot{w}_o^2(t)d_o/Vg^2)$$

one would obtain the expression for the vibration "shock" level in dB (re. a "funny unit"). This metric would, of course, scale the vehicle speed and reference distance effects. However, it was beyond the scope of the project to pursue this particular topic. It is the author's opinion that the vibration "shock" level is the most appropriate metric for describing the traffic-induced vibration problem.

The result of Equation (4.2-3) is the central result of this section.

4.3 EVALUATION OF INTEGRALS

To obtain an estimate of the equivalent vibration level at the receiver, it is required to evaluate the integrals described in Section 4.2.

These integrals have the general form:

$$I_n(\beta) = \int_0^\infty EXP(-n\beta(1+a^2)^{\frac{1}{2}})(1+a^2)^{-n/2}da \qquad (4.3\text{-}1)$$

where $n = 1, 2, \ldots$

$\beta = 2\eta\overline{d}$

a is a dimensionless variable ($x/\overline{d}$, $Vt/\overline{d}$, or α)

The integration limits indicated above are for a "semi-infinite" roadway or, alternately, proportional to half the vibration energy transmitted from the vehicle to the receiver during a single pass-by.

To evaluate the integral, one makes the change of variable, $Z^2 = (1+a^2)$, and begins looking up definite integrals (See Reference 4-2).

The general form of the integral is

$$I_n(\beta) = \int_1^\infty EXP(-n\beta Z)Z^{1-n}(Z^2-1)^{-\frac{1}{2}}dZ \qquad (4.3\text{-}2)$$

For n=1, the integral can be evaluated explicitly (4-2, p. 322, Integral 3.387/3) as

$$I_1(\beta) = \int_1^{\infty} EXP(-\beta Z)(Z^2-1)^{-\frac{1}{2}}dZ = K_o(\beta) \simeq e^{-\beta}\sqrt{\pi/2\beta} \qquad (4.3\text{-}3)$$

where $K_o(\beta)$ is the modified Bessel Function of the third kind of order zero.

For n=2, the integration cannot, apparently, be obtained in explicit form. Numerical integration is apparently required; however, numerical integration would obscure the physical understanding of the problem. Additionally, numerical integration would require an extensive tabulation of numbers to cover the range of the parameter β. The following technique is used to obtain an approximate expression for the integral of Equation (4.3-1) for n=2. This result is due to the author's associate D. F. Lam.

From Equation (4.3-1) for n=1 it is noted that

$$\frac{d}{d\mu}\int_1^{\infty} EXP(-\mu Z)Z^{-1}(Z^2-1)^{-\frac{1}{2}}dZ = -\int_1^{\infty} EXP(-\mu Z)(Z^2-1)^{-\frac{1}{2}}dZ \qquad (4.3\text{-}4)$$

The integral on the right hand side of Equation (4.3-4) is simply $-K_o(\beta)$ from Equation (4.3-3). Then, the integration, for n=2, is:

$$I_2(\beta) = \int_{\mu}^{\infty} K_o(x)dx \qquad (4.3\text{-}5)$$

where the constant of integration is zero.

The integral of $K_o(x)$ cannot be easily evaluated either. As an approximation, however, the result of Equation (4.3-3) is used to obtain:

$$I_2(\beta) \simeq \pi ERFC(\sqrt{2\beta})/\sqrt{2} \qquad (4.3\text{-}6a)$$

or

$$I_2(\beta) \simeq \sqrt{\pi/2}EXP(-2\beta)/\sqrt{2\beta} \qquad (4.3\text{-}6b)$$

$$\beta > 1.5$$

where ERFC(x) is the complementary error function.

It is difficult to state the extent of the approximations used above as related to numerical accuracy. However, the results do appear to have the proper functional form. That is, the intensity decreases with increasing distance as an exponential divided by the square root. This is like a "point source" attenuation. Since this attenuation "law" applies to the traffic flow, "point source" attenuation of traffic flows is the predicted result. This prediction is basic to the traffic-induced vibration problem. That is, each source and its vibration distance attenuation is preserved as a distinct source in the traffic flow. This is observed experimentally in Appendix VI.

5.0 TRAFFIC FLOW MODEL

This section describes the formulation of a traffic flow model to simulate the generation of ground vibration by continuously flowing traffic. A mixture of vehicles is assumed by the model. The vehicle mix is based upon the vibration emission characteristics of the vehicles. Based upon the results of Sections 3 and 4, basic source emission vibration levels and propagation "laws" are presented in functional form. These source vibration levels are classified by pavement surface roughness as:

- Bump Level, Equation (3.2-4)
- Random Level, Equation (3.2-9)

The propagation of vibration away from the roadway depends upon the type of vibration source. For a bump, the propagation is the "point" source relation given by Equation (4.1-1) where the distance is from the bump to the receiver. This distance does not vary with time. For continuous traffic flows, the "line" source attenuation given by Equation (4.2-3) is the appropriate propagation law.

5.1 BUMP IRREGULARITIES

For the evaluation of reciever vibration resulting from a traffic flow encountering a bump, each tire contact with the bump generates a vibration pulse that propagates from the bump to the receiver. The number of pulses is simply the number of axles times the number of vehicles. The peak impulse or impact vibration level, $(L_o)_{max}$, at a distance, d_o, from the bump is the reference vibration level. (The result of Equation (3.2-4) applies at the bump location.) From Equation (4.1-1), the receiver peak impulse or impact level for a single tire contact is:

$$L(d)_{max} = (L_o)_{max} + 10\log(d_o/d) - 20\log(e)\eta(d-d_o) \qquad (5.1\text{-}1)$$

This result assumes that expermental data is available to establish values of $(L_o)_{max}$ for vehicle types (and axles). This data is generally not available. The results of Equation (3.2-4) may be used to estimate the peak impulse or impact level at the bump. The appropriate distance to use is the distance from the bump to the receiver. In terms of the impact factor, IF, and the axle weight, W_{axle}, the peak impulse or impact level at the receiver is

$$L(d)_{max} = 20\log(IF)+20\log(W_{axle}/W_f) - 10\log(d)-20\log(e)\eta d+6 \quad \text{dB (re. } 1g_{peak}) \qquad (5.1\text{-}2)$$

To use this result, one would predict the level and determine the number of impacts per day based upon the axle count. Criteria relating vibration level to number of occurrences per day is presented in Reference (5-1). From Equation (5.1-2) it is obvious that the most heavily loaded axles are the most important. Impact Factors are discussed in Section 2.3.1.

5.2 CONTINUOUS TRAFFIC FLOW

The determination of environmental impact due to vibration generated by continuous traffic flow is basically simple. The formulation of a traffic flow vibration model is identical to traffic flow noise models. The approach taken here to evaluate the vibration from complex traffic flows is based upon the concept of an equivalent vibration level. The equivalent vibration level of the complex traffic flow is then determined as an intensity or energy accumulation of all vehicle sources. The only difference between this model and comparable traffic flow noise models (5-2, -3) is that technical details of the propagation require special consideration (See Section 4.2).

Criteria for evaluating the effect of traffic-induced vibration are presented in Reference 5-1. These criteria and the levels associated with traffic-induced vibration problem indicate that only the intermittent peak levels exceeding certain criteria limits are potentially annoying. For traffic-induced vibration, each vehicle exhibits a characteristic peak even for dense traffic flows. Since heavy vehicles generally omit the highest vibration levels in a traffic flow, one is able to consider only the heavy vehicles. Further, since the criteria indicate that a few intrusions (less than 10 per day) of perceptible vibration may result in annoyance, one may decompose the traffic flow model into a "single event" analysis and still obtain an accurate prediction of annoyance.

Whereas traffic noise may generally increase the ambient noise level of an area, it does not appear that traffic-induced vibration generally increases the "ambient" vibration level of a community. The traffic flow vibration model presented below considers these aspects of the problem.

The metrics used to quantify the traffic-induced vibration problem for mixed traffic flows are the equivalent vibration level, L_e, and the percentile levels such as L_{10}, L_{05}, etc. Since the peak vibration levels are the problem, the extreme vibration percentile levels are the most important.

For dense traffic flows, it is assumed that the distribution of vibration amplitudes during a time period T is Gaussian. (The validity of this assumption appears to be as accurate for traffic-induced vibration as it is for traffic noise.) The vibration amplitude distribution is then completely defined by the mean vibration level, L_{50}, and the standard deviation of the vibration level, σL.

The mean vibration level is defined in terms of the energy mean vibration level and the standard deviation as

$$L_{50} = L_e - 0.115\sigma_L^2 \qquad (5.1\text{-}3)$$

$$\sigma_L = (1\text{-}/\ln(10))\sqrt{\ln(1+\kappa_2)} = 4.343\sqrt{\ln(1+\kappa_2)}$$

where κ_2 is called the cumulant.

In terms of either the mean vibration level, L_{50}, or the energy mean vibration level, L_e, the percentile vibration levels are:

$$L_{10} = L_{50}+1.28\sigma_L \quad \text{(level exceed 10\% of time)}$$
$$L_{05} = L_{50}+1.648\sigma_L \quad \text{(level exceeded 5\% of time)}$$
$$L_{01} = L_{50}+2.33\sigma_L \quad \text{(level exceeded 1\% of time)} \qquad (5.1\text{-}4)$$
$$L_{0.1} = L_{50}+3.09\sigma_L \quad \text{(level exceeded 0.1\% of time)}$$

These results apply to a traffic flow comprising a mixture of vehicles of different gross weights.

The requirement is to calculate the equivalent level, L_e, and the cumulant κ_2 in terms of the basic vehicle vibration emission levels and the traffic flow parameters.

As described in Section 4, each roadway may be considered as infinite in length for the highway vibration problem. Using the basic emission/propagation relationship given by Equation (4.2-1) and the theory of Reference 5-2, the total equivalent vibration level at a receiver may be estimated.

For a single lane of traffic comprising several vehicle types (denoted by a subscript i) the expressions for the equivalent vibration level, L_e, and the cumulant using the above procedure are:

$$L_e = 10\log(d_o \mathrm{EXP}(2\eta d_o) I_e) \qquad (5.1\text{-}5a)$$

and $$\kappa_2 = (I_2(2\eta\bar{d})/\bar{d} I_e^2)\sum_i \lambda_i 10^{\tilde{L}_{oi}/5} \qquad (5.1\text{-}5b)$$

where $I_e = I_1(2\eta\bar{d})\sum_i \lambda_i 10^{L_{oi}/10}$

$I_1(2\eta\bar{d})$ is the integral of Equation (4.3-1) for n=1

$\lambda_i = \bar{N}_i/(VT)$ is the vehicle concentration

L_{oi} is the reference vibration emission level

$I_2(2\eta\bar{d})$ is the integral of Equation (4.3-1) for n=2

The variability of the reference emission level L_{oi} may be considered if one assumes that the distribution of values of L_o are Gaussian. For a regression analysis, the mean or expected value of the reference emission level, $\overline{L}_o$, is obtained along with the standard error associated with the regression. Thus, the value of the reference emission level is expressed as an energy average as

$$L_{oi} = \overline{L}_{oi}+0.115\sigma^2_{oi} \quad (5.1\text{-}6)$$

The value of L_{oi} given by Equation (5.1-6) is the value to be used in Equations (5.1-5). In Equation (5.1-6), the following value must be used:

$$\tilde{L}_{oi} = \overline{L}_{oi}+0.230\sigma^2_{oi} \quad (5.1\text{-}7)$$

The result of Equation (5.1-5) applies to a single traffic lane. This is the basic formulation of the traffic flow model. The vibration emissions from traffic seem to depend upon pavement surface roughness. Pavement surface roughness may vary from lane to lane on the same structural slab. Hence, the total equivalent vibration level and the cumulant at the receiver location from traffic moving on the same pavement slab is obtained from Equations (5.1-5) as:

$$L_e = 10\log(\sum_j 10^{L_{ej}/10}) \quad (5.1\text{-}8a)$$

and $$\kappa_2 = 10\log(\sum_j \kappa_{2j}) \quad (5.1\text{-}8b)$$

The term L_{ej} is obtained from Equation (5.1-5a). The term κ_{2j} is obtained from Equation (5.1-5b). Each term comprises the traffic conditions particular to that lane.

By using the approximation of Section 4.3 and doing some algebra the results of Equations (5.1-5) may be formulated in a more attractive format. This is done in Reference 5-1.

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REPORT NO. FHWA-RD-

IMPACT FROM TRAFFIC-INDUCED VIBRATIONS

APPENDIX VI

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February 1978

FINAL REPORT

PREPARED FOR:

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
OFFICE OF RESEARCH
ENVIRONMENTAL DESIGN AND CONTROL DIVISION
WASHINGTON, D. C. 20590

APPENDIX VI

FIELD MEASUREMENTS
OF
TRAFFIC-INDUCED
VIBRATION

APPENDIX VI

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APPENDIX VI

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APPENDIX VI

This appendix describes the field measurements conducted under Task D. These measurements and the resulting data were used interactively with the model formulation and the development of engineering guidelines to quantify the problem of traffic-induced vibration. At the inception of this project, only two technical publications were available in the open literature that discussed the measurement of traffic-induced vibration (6-1, -2)*

The only aspect of the problem that would be quantified at the initiation of the field measurement program was that traffic-induced vibration was characterized by a low-level, low frequency, transient vibration. The modeling effort described in Appendix V had only been underway a few months and the complaint data described in Appendix II had just begun to be received.

The first problem encountered in identifying potential sites for measuring traffic-induced vibration was an apparent reluctance of public officials to have measurements taken. The candidate sites were, of course, identified by a complaint concerning traffic-induced vibration.

In addition to the criteria for selecting a site for evaluating complaints concerning traffic-induced vibration, it was desired to evaluate distance attenuation effects and look at traffic speed and flow effects. The budget, however, was not so generous to allow all aspects of the problem to be investigated. Indeed, at the beginning of the task it appeared that almost any parameter might be a variable. In addition, criteria for evaluating the severity of the vibration levels measured was only roughly quantified (6-3).

6.1 BASIC SITE CHARACTERISTICS

The site vibration measurements described in this appendix were taken at eight sites. Three sites were selected to evaluate human perception of vibration and building response to the vibration. One site was selected to measure

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* Numbers in ( ) denote references located at the back of this section.

traffic vibration from high speed continuous traffic flow to determine propagation characteristics of the traffic-induced vibration and vehicle interaction effects. One site was selected at which the effectiveness of a trench was evaluated for abatement of traffic-induced vibration. Four configurations of the "trench" site were evaluated: no trench, open trench, trench filled with sawdust, and trench filled with water saturated sawdust.

Specifically, the sites studied are as follows:

Site 1. Residential Detached Single Family Dwelling on a local urban street carrying bus traffic.

Site 2. Residential Detached Single Family Dwelling on an urban arterial carrying intermittent flow of heavy trucks.

Site 3. Residential Detached Single Family Dwelling on a local urban street carrying intermittent flow of heavy trucks.

Site 4. Interstate Traffic carrying a continuous flow of high speed heavy trucks.

Site 5. Trench Site before trench was excavated.

Site 6. Trench Site with open trench.

Site 7. Trench Site with trench filled with dry sawdust. (This is a cheap "fill" material common to the area.)

Site 8. Trench Site with sawdust fill saturated with water.

The instrumentation, measurement procedure, and data analysis techniques are described first. An overview of the data is presented to illustrate the basic characteristics of traffic-induced vibration. Finally, the data for each site is presented and discussed. Criteria for evaluating the significance of the impact are presented in Reference 6-4.

6.2 INSTRUMENTATION, MEASUREMENT PROCEDURE, AND DATA ANALYSIS TECHNIQUES

This section describes the instrumentation, measurement procedures, and data analysis techniques used to obtain the traffic-induced vibration reported.

6.2.1 Instrumentation

The portable data acquisition system utilized for the field measurement program is illustrated in Figure 6.2-1. This system is capable of recording simultaneously six channels of vibration data in the amplitude range of 2×10^{-6}g to 1.0g and a linear frequency response of 2 Hz to 1000 Hz. System calibration is achieved utilizing an internal calibration signal from the charge preamplifiers. The dynamic range of the system is approximately 50 dB with 10 dB incremental amplification using the charge amplifiers. The system power supply is from a portable 1.5 KW generator. The cable length of 200 feet per channel was selected as a compromise between portability and cost. One channel of direct record acoustic data was available for voice identification and data acquisition as required.

6.2.2 Measurement Procedure

The basic measurement procedure comprised the location and monitoring of the accelerometers and the selection of appropriate gain settings on each channel of instrumentation. For an accelerometer located on the ground surface a phenolic base plate was used. This base plate is illustrated in Figure 6.2-2. The surface soil comprising the root system and or pebbles was carefully removed and leveled. The base plate was staked to the ground using common "gutter spikes" and leveled. The accelerometer was screwed on to the base plate using the exposed stud. The base plate performed two functions: the firm attachment of the accelerometer to the ground and the electrical insulation of the system to prevent "ground looping".

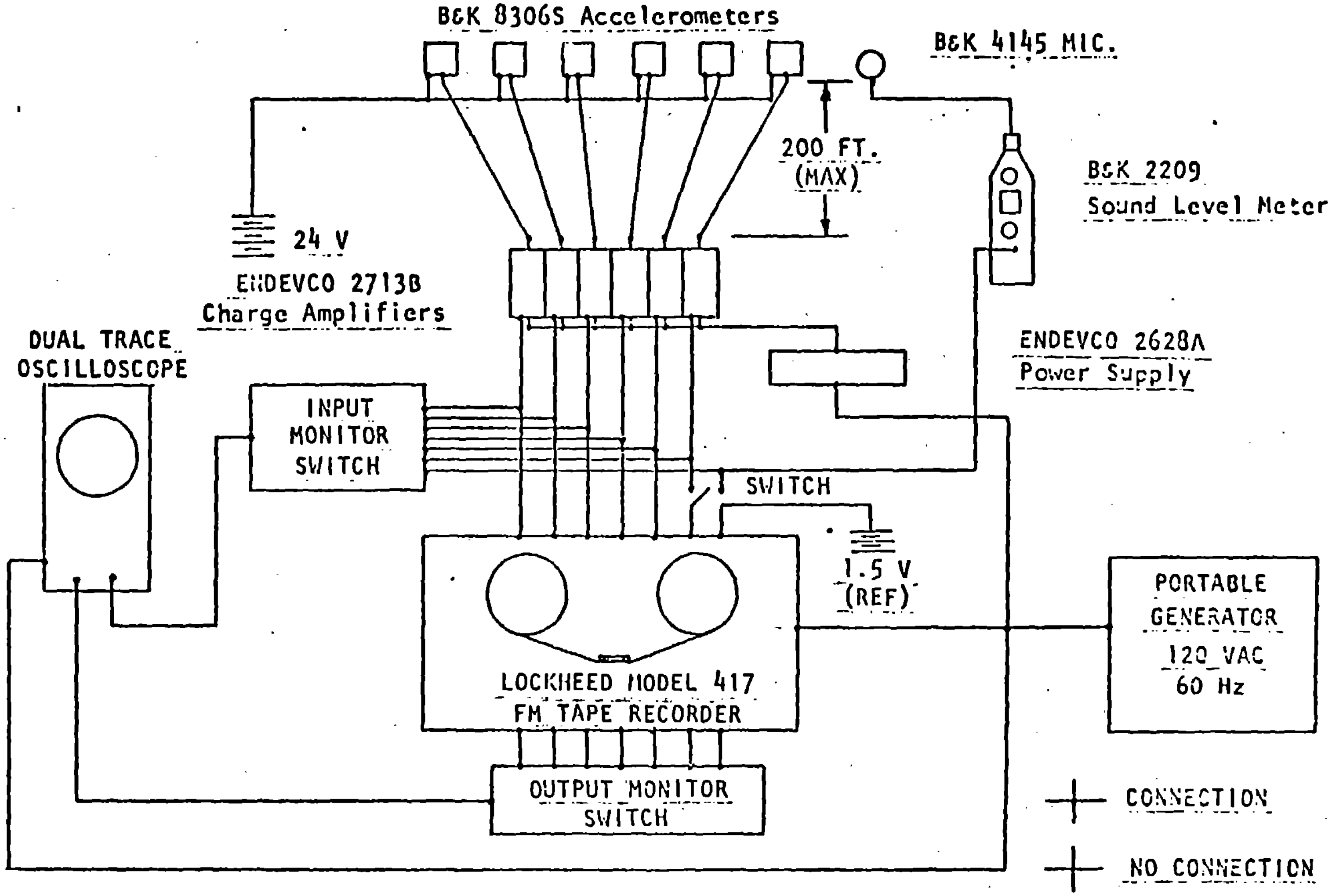


FIGURE 6.2-1 DATA ACQUISITION SYSTEM FOR HIGHWAY VIBRATION MEASUREMENTS

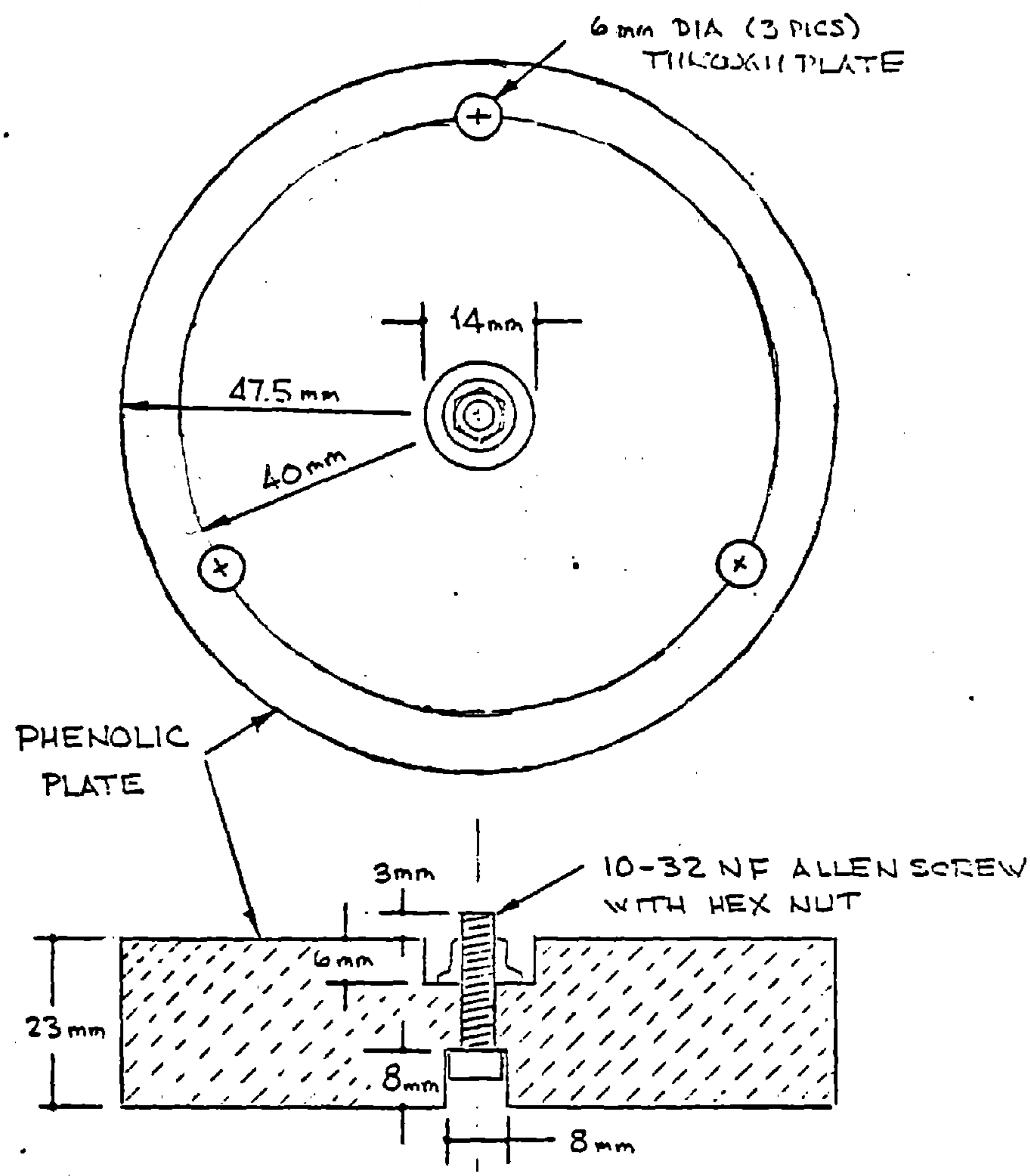


FIGURE 6.2-2 ACCELEROMETER SUPPORT PLATE
FOR GROUND VIBRATION

For an accelerometer located in a building, the accelerometers were attached to horizontal surfaces (floors, beams, window ledges, etc.) using "supervisor" or "double face" adhesive pads. Figure 6.2-3 presents photographs of typical accelerometer installations.

Calibration of the instrumentation comprised the tape recording of the internal calibration signal from each charge amplifier. Calibration recordings were recorded for all channels at the beginning and end of each tape reel and before and after the relocation of any or all components of the system.

The instrumentation on each channel was numbered from 1 to 6. For each recording taken during the measurement program, the accelerometer, cables, charge amplifier, and data track on the tape recorder were always the same component.

The tape recording of data initially comprised "single event" data and "continuous" recording. Figure 6.2-4 illustrates continuous level recording for urban street traffic. Figure 6.2-5 illustrates a continuous level recording for Interstate traffic. Each tape recording was identified by sequential event number.

6.2.3 Data Analysis Techniques

The analysis techniques used for the field test data comprised the following:

- Amplitude or Level Distribution Analysis for Each Event for the Unfiltered Vibration Data
- 1/3 Octave Band Amplitude or Level Distributions for Selected Events
- Digital Data Analysis Comprising Power Spectral Density and Time History Plots for Selected Events. (These analyses were perforemd at the NASA Langley Research Center Computing Facilities under agreement with the Federal Highway Administration.)

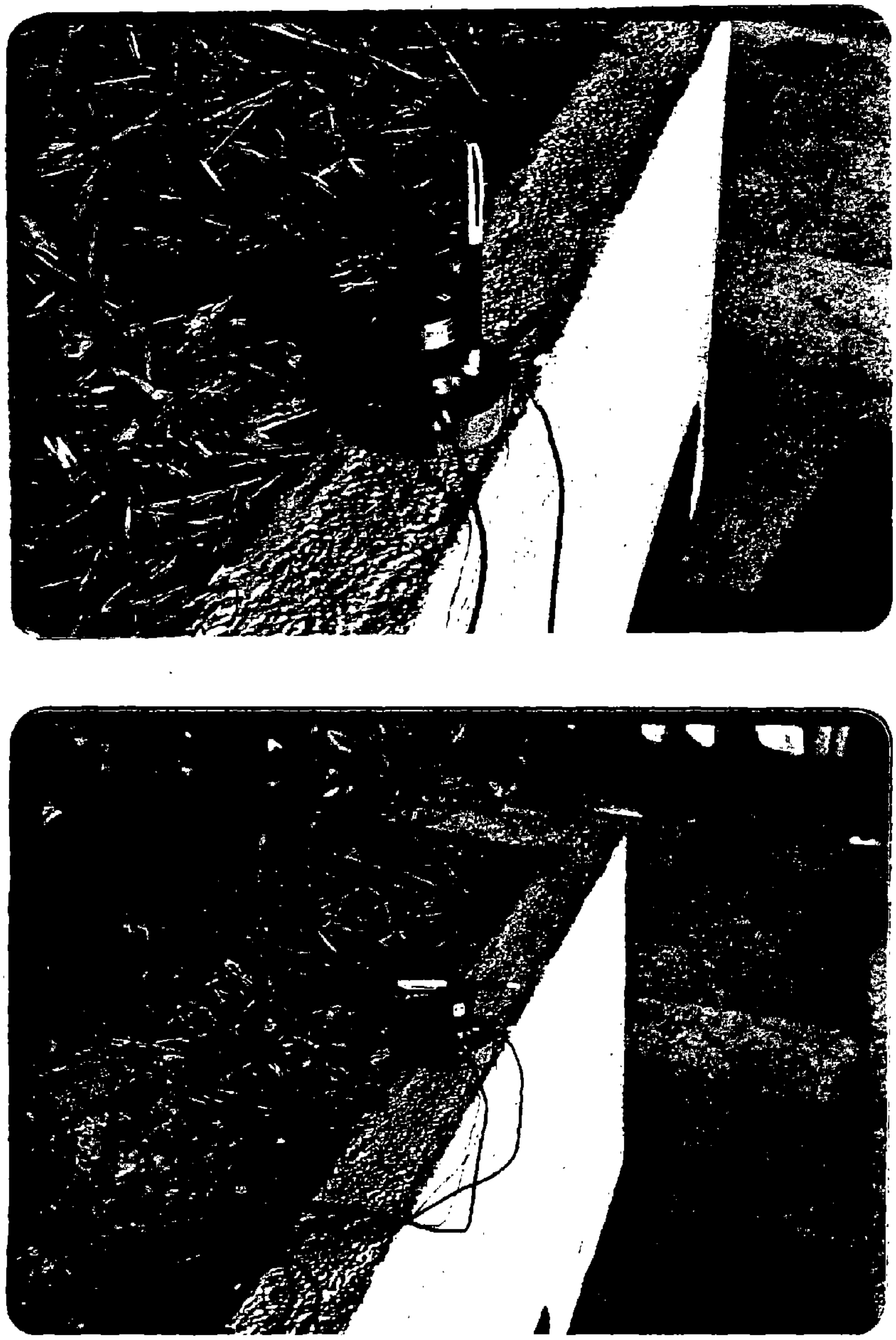


FIGURE 6.2-3 PHOTOGRAPHS OF TYPICAL ACCELEROMETER INSTALLATIONS

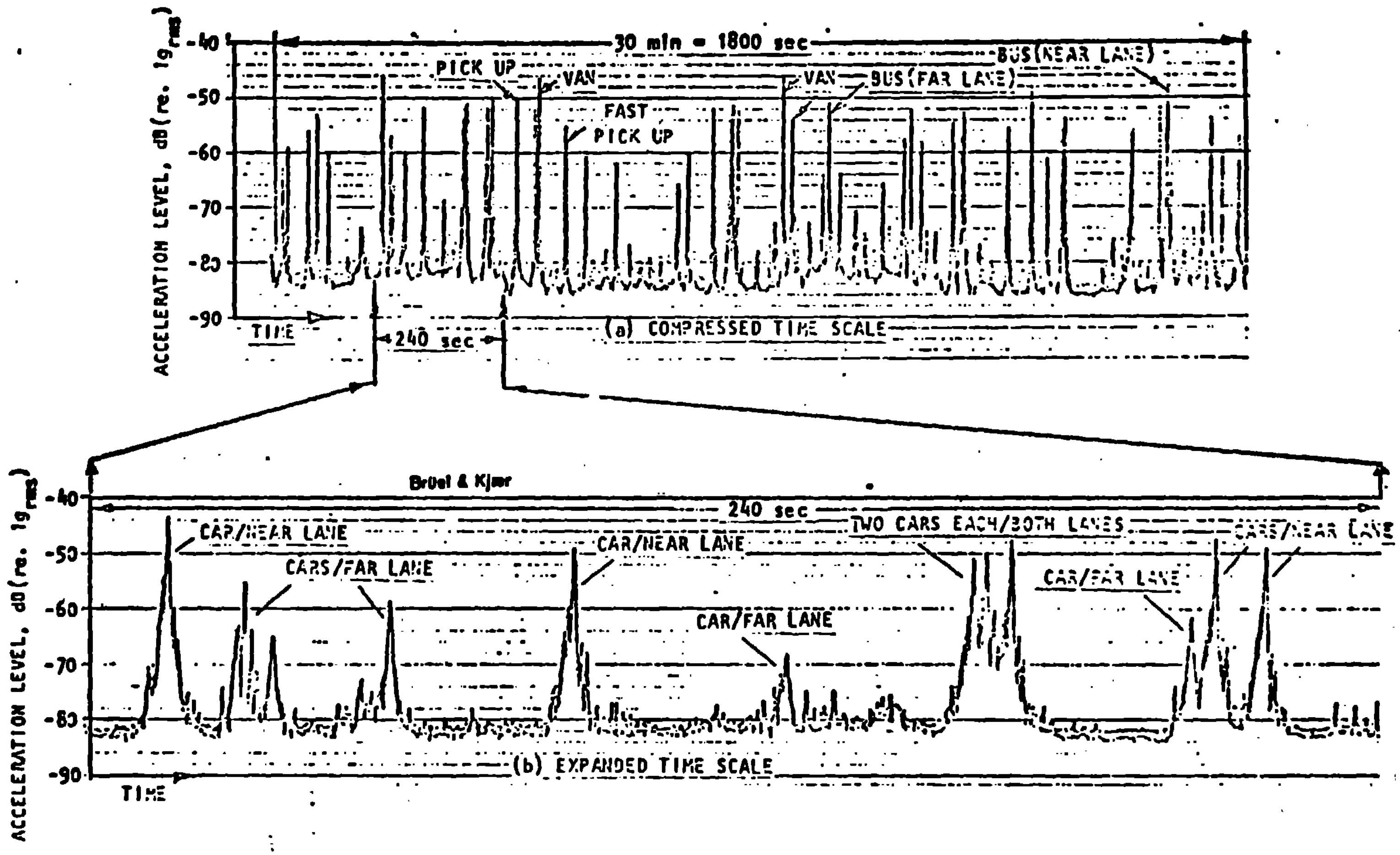
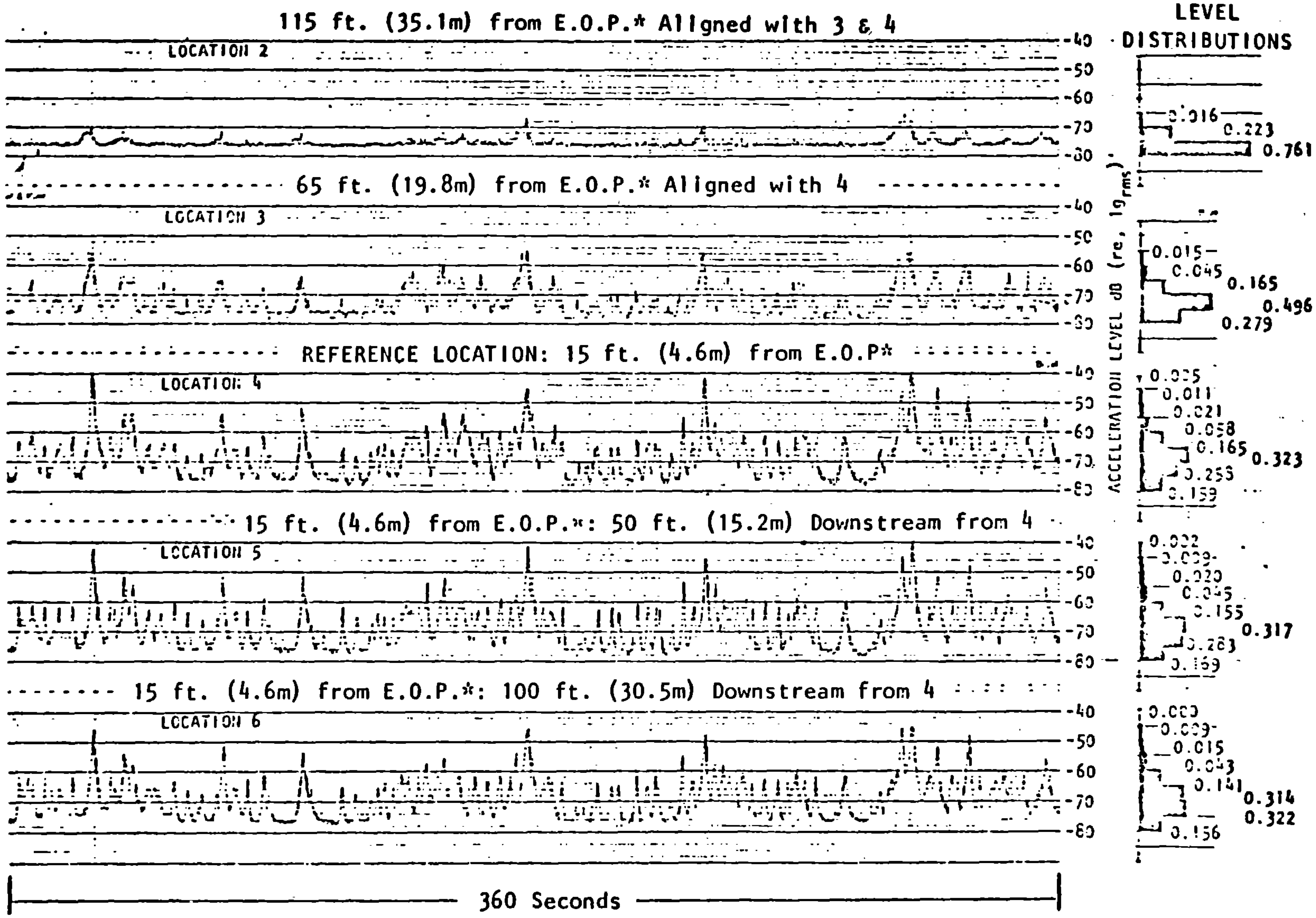


FIGURE 6.2-4 TRAFFIC-INDUCED GROUND VIBRATION: RESIDENTIAL STREET



* E.O.P. denotes Edge Of Pavement

FIGURE 6.2-5 TRAFFIC-INDUCED GROUND VIBRATION: INTERSTATE HIGHWAY

Figure 6.2-6 presents a typical ground motion acceleration time history using the digital data analysis with the inset in the figure indicating the overall level recording of the event. Typical power spectra obtained using the digital data analysis are presented in Figures 6.2-7 and 6.2-8.

The overall and 1/3 Octave Band level distribution analyses were performed, laboriously, using the system illustrated in Figure 6.2-9. An example of the time-averaged 1/3 Octave Band Spectral Data using this system is illustrated in Figure 6.2-10.

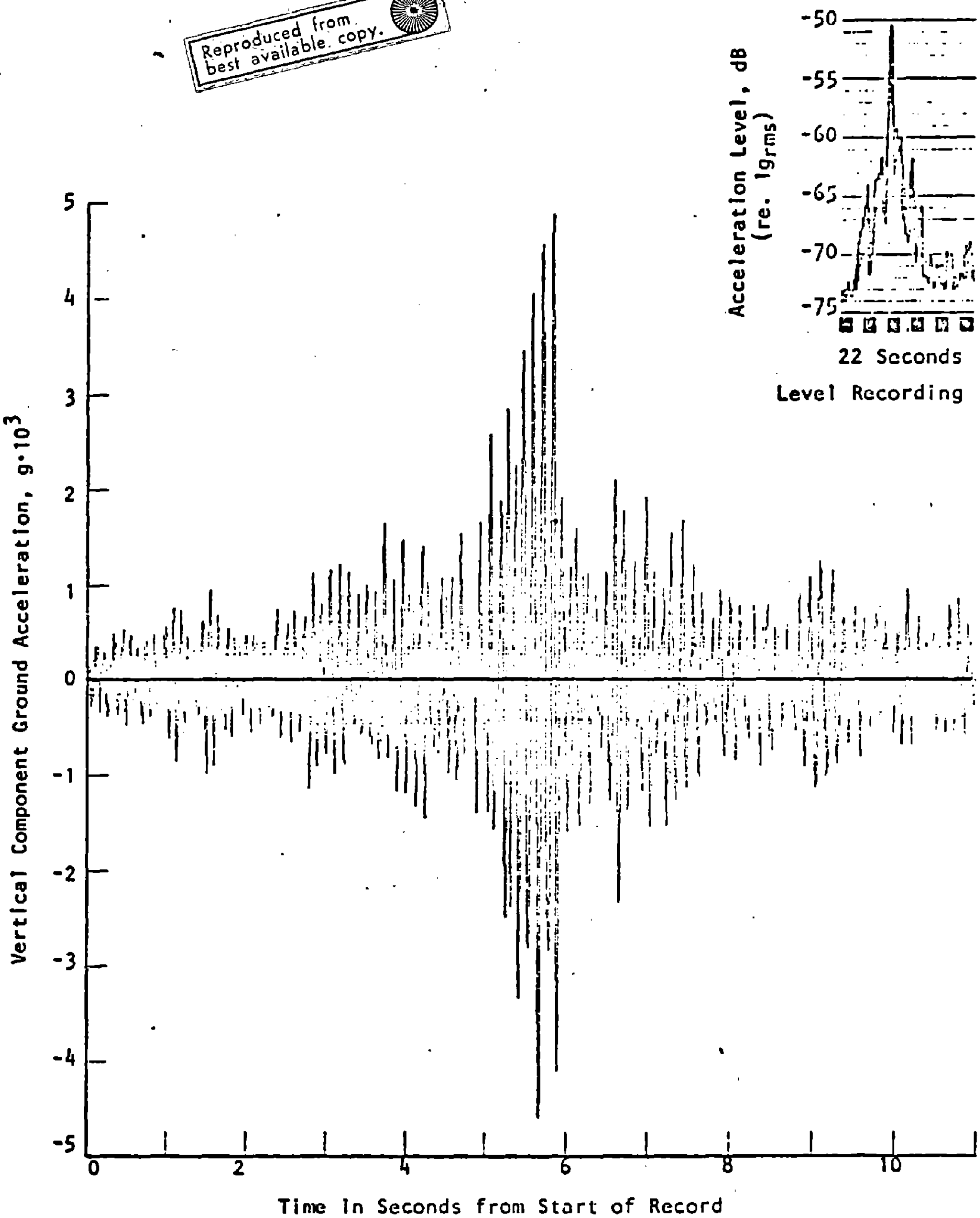


FIGURE 6.2-6 TYPICAL TRAFFIC-INDUCED GROUND VIBRATION TIME HISTORY

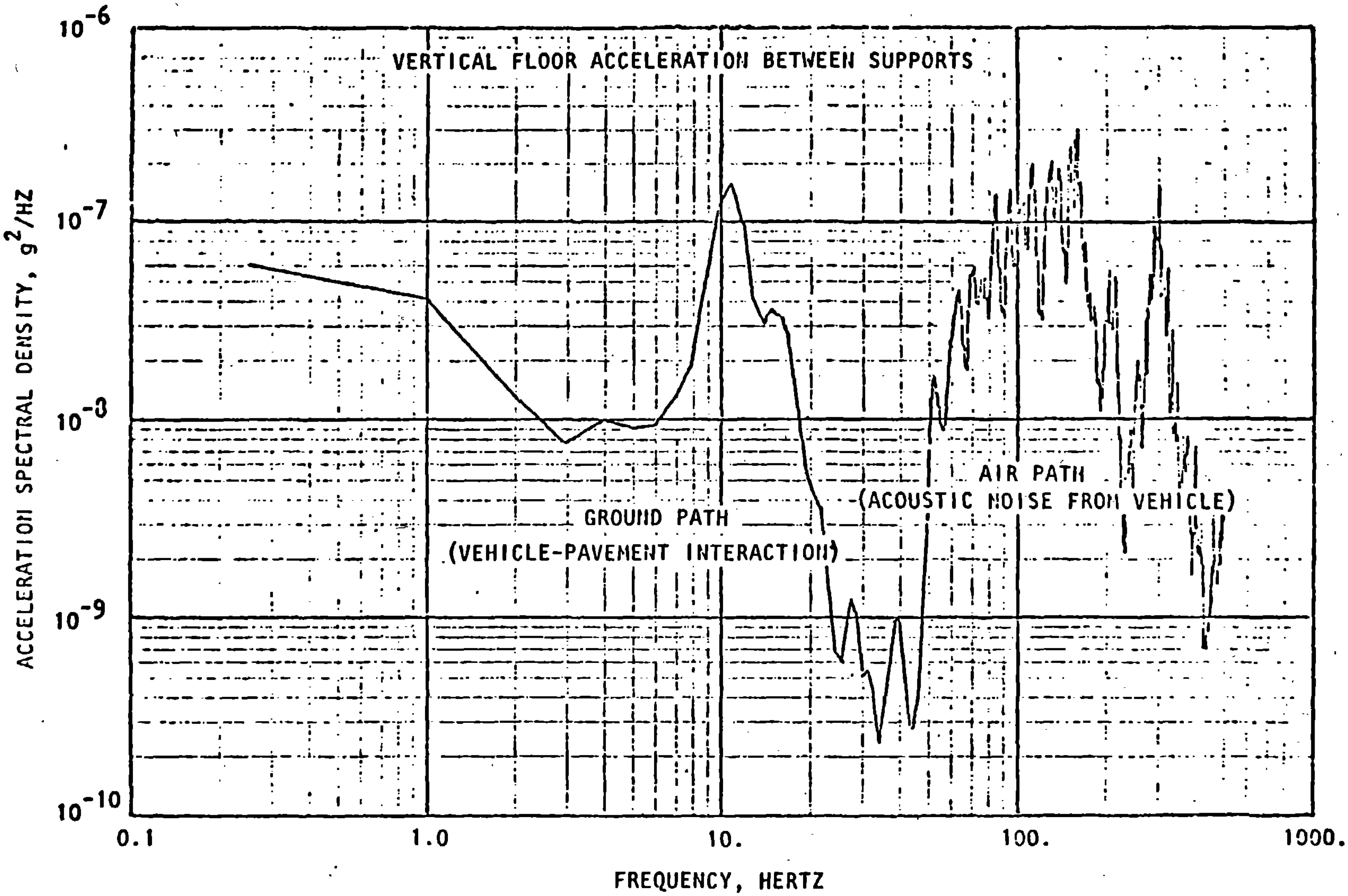


FIGURE 6.2-7 BUILDING RESPONSE TO COMBINED TRAFFIC NOISE AND VIBRATION

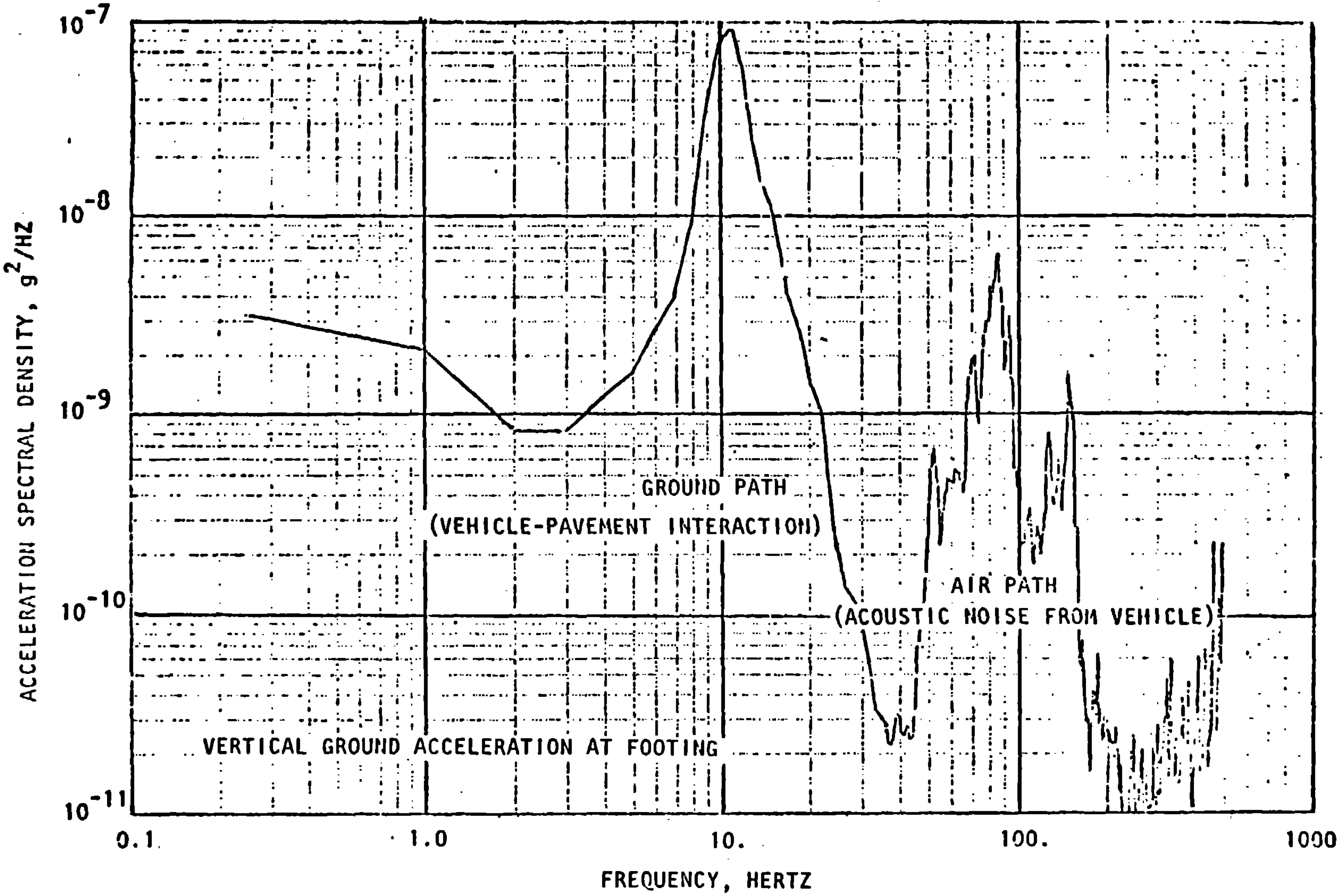


FIGURE 6.2-8 GROUND MOTION RESPONSE TO COMBINED TRAFFIC NOISE AND VIBRATION

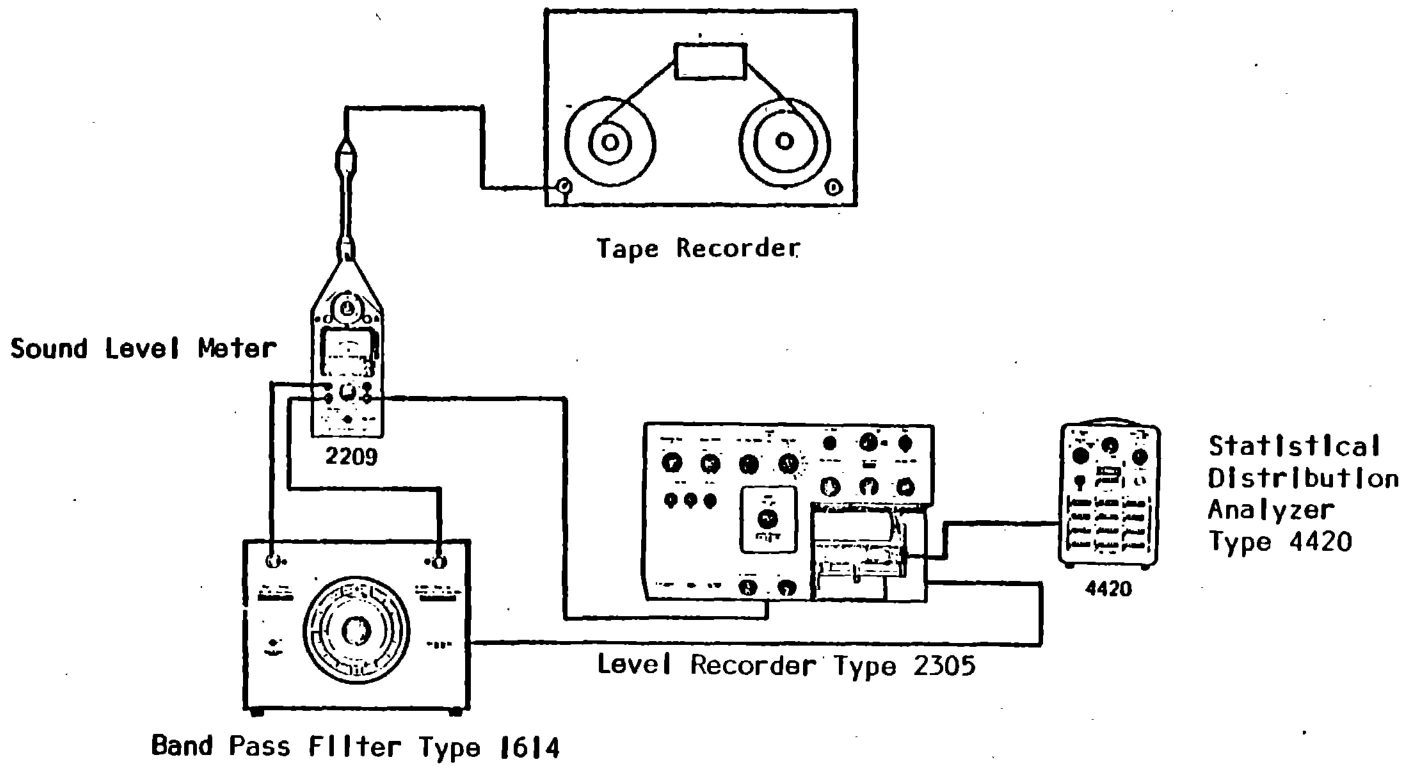


FIGURE 6.2-9 DATA REDUCTION SYSTEM: TIME-AVERAGED SPECTRAL ANALYSIS

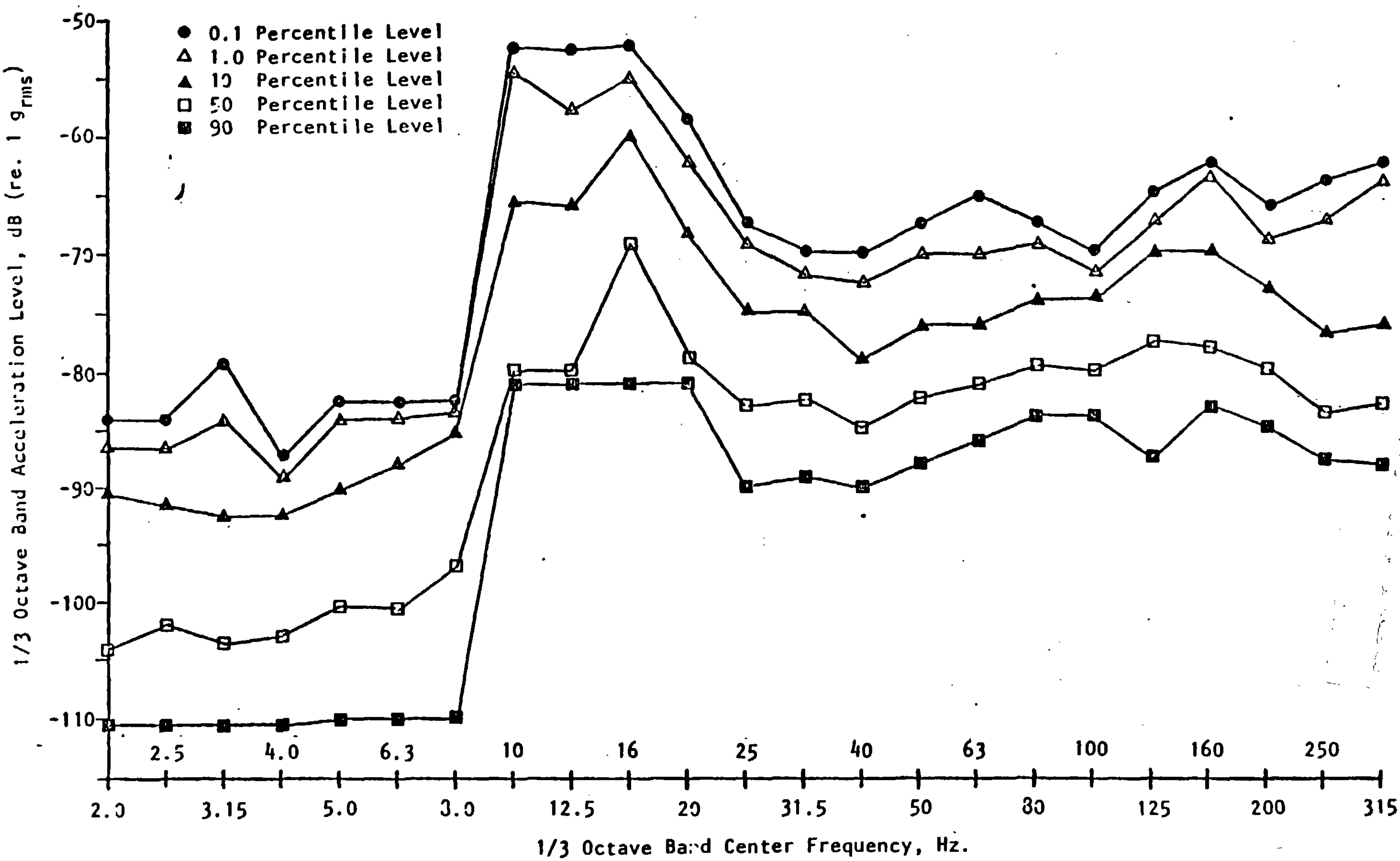
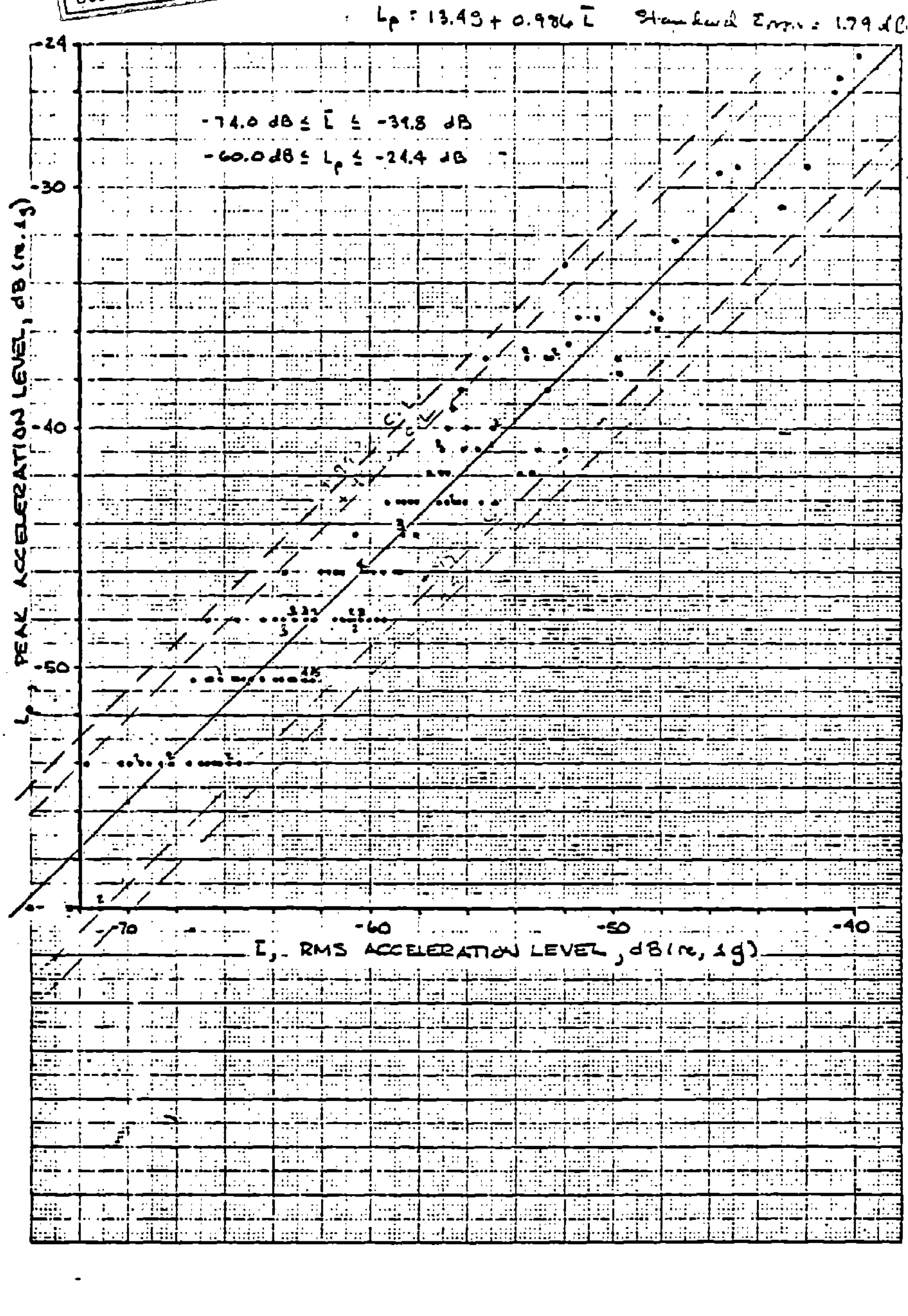
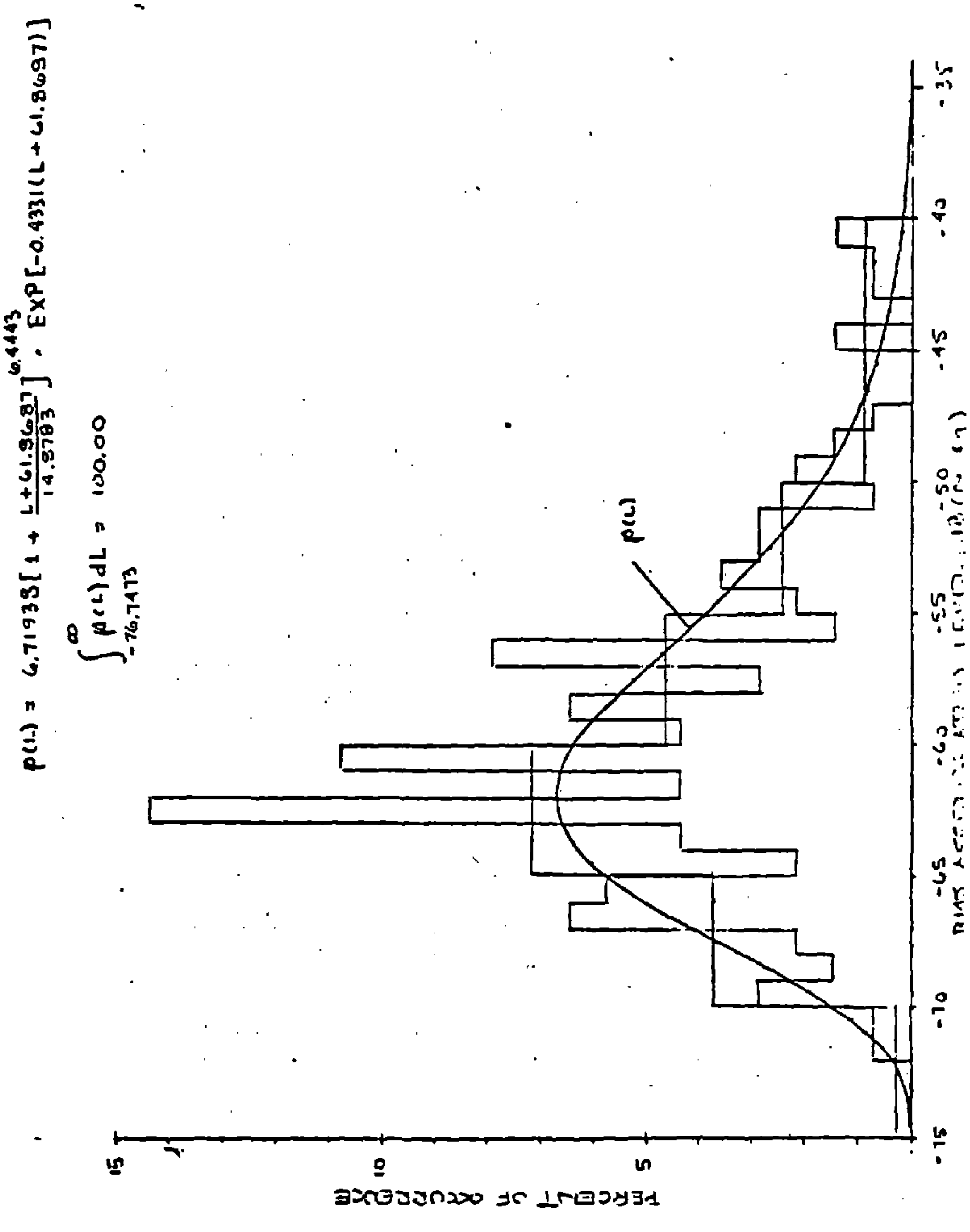
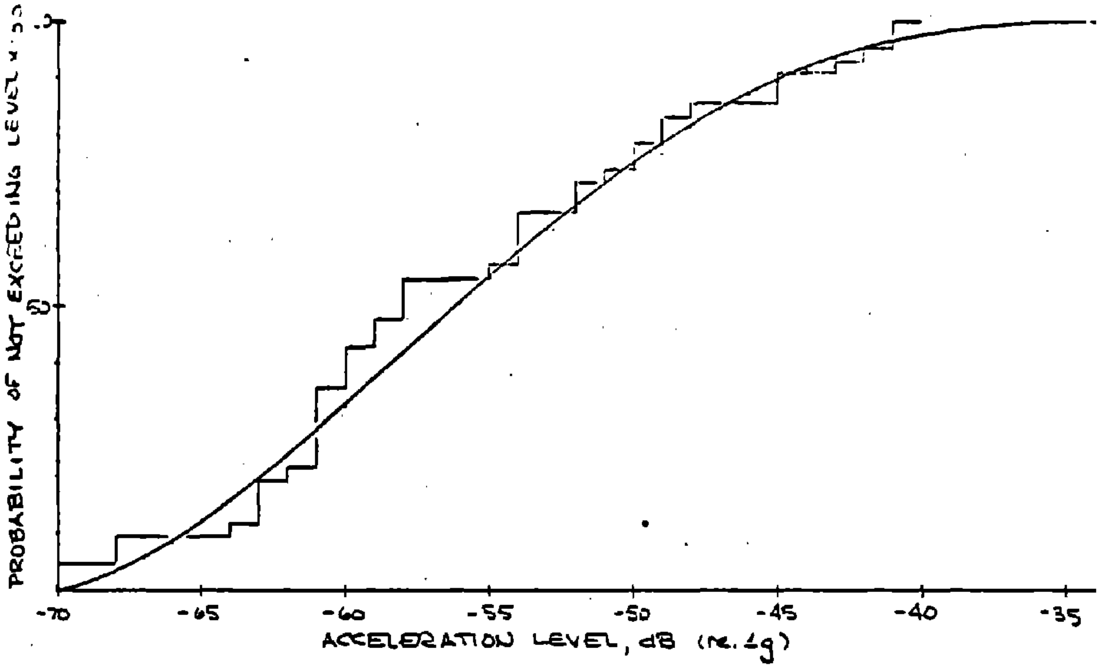


FIGURE 6.2-10 TRAFFIC-INDUCED VIBRATION SPECTRA: BEDROOM FLOOR

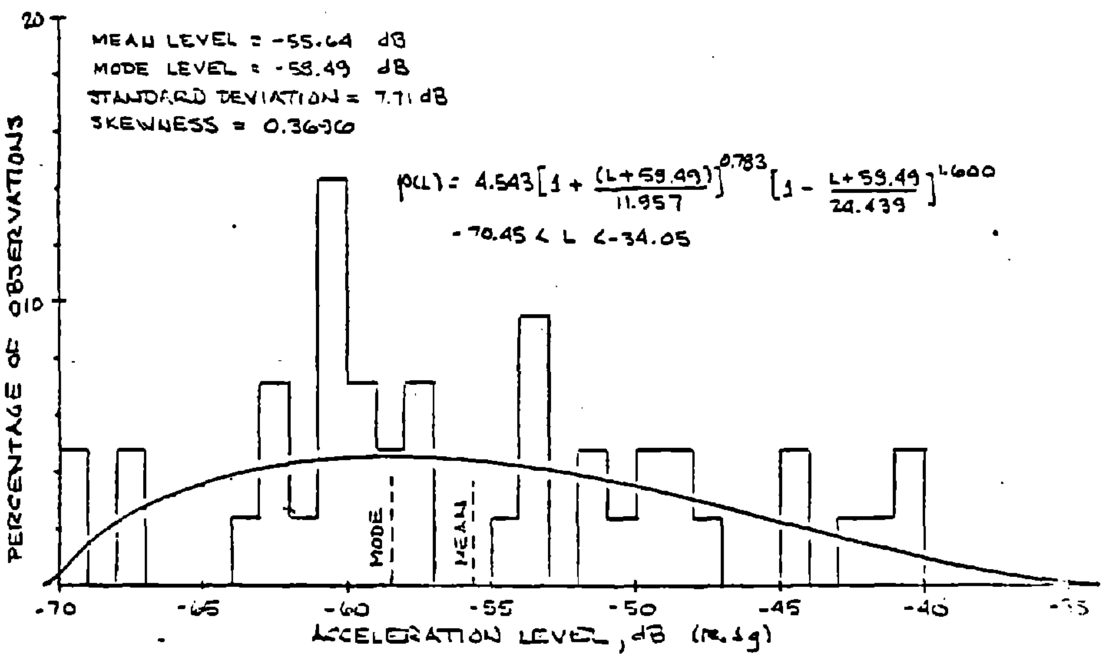

Lp = 13.49 + 0.986 L̄   Standard Error = 1.79 dB
-74.0 dB ≤ L̄ ≤ -39.8 dB
-60.0 dB ≤ Lp ≤ -24.4 dB
-24
-30
-40
-50
Lp, PEAK ACCELERATION LEVEL, dB (re. 1g)
-70
-60
-50
-40
L̄, RMS ACCELERATION LEVEL, dB (re, 1g)



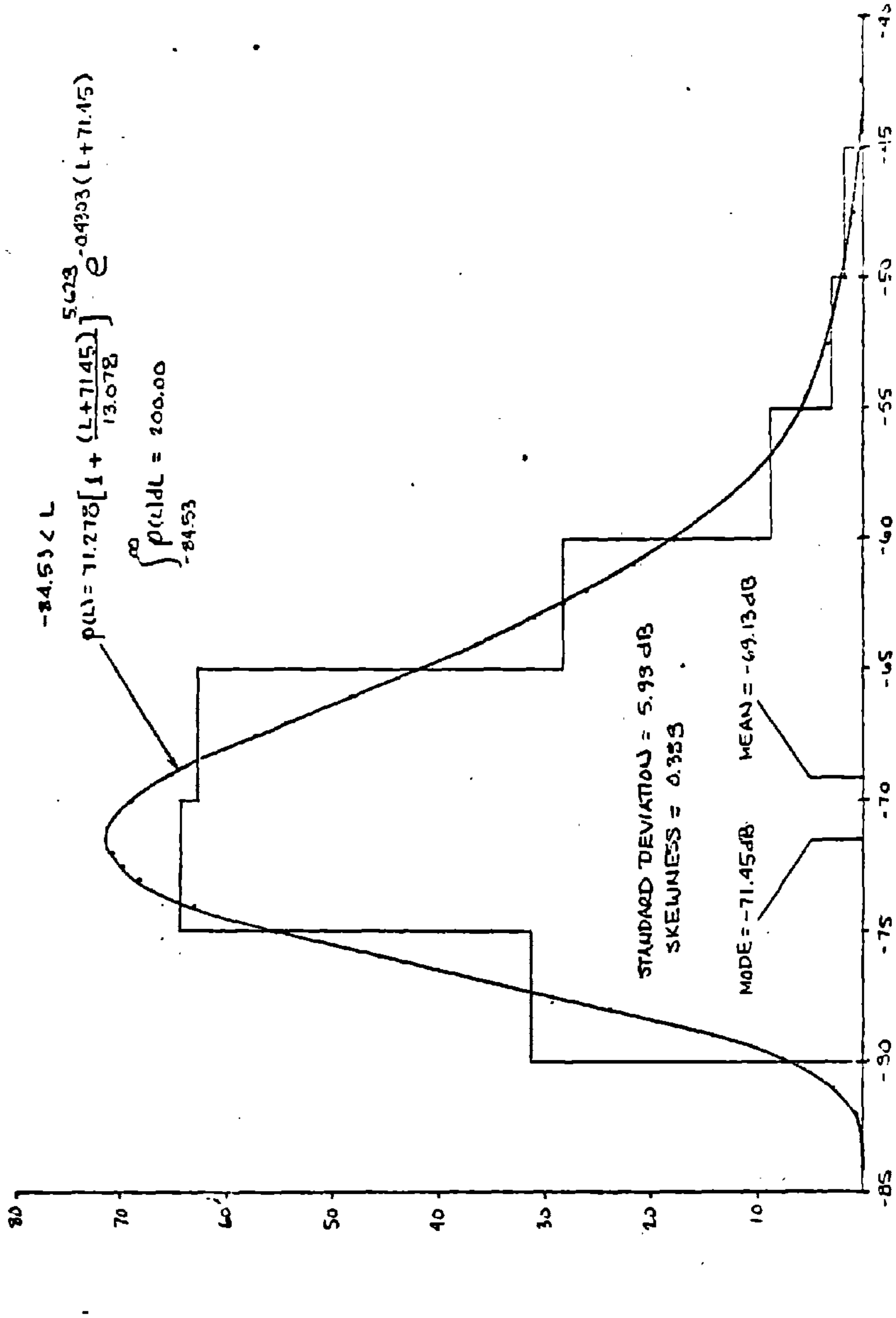
p(L) = 6.7193[1 + (L+61.9687)/14.8783]^6.4443 · EXP[-0.4331(L+61.8697)]
∫ p(L) dL = 100.00
-76.7473
∞
p(L)
PERCENT OF OCCURRENCE
15
10
5
-75
-70
-65
-60
-55
-50
-45
-40
-35



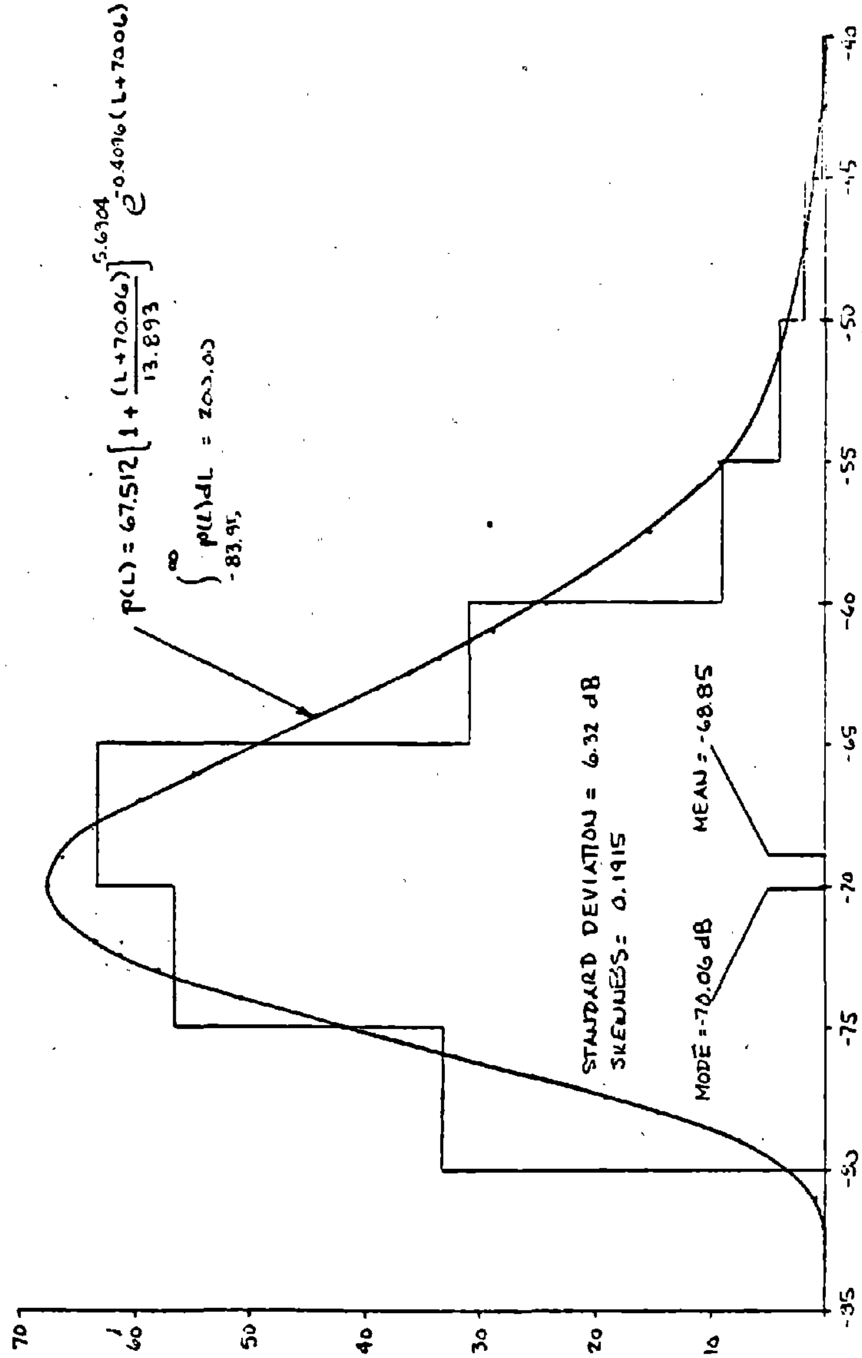
PROBABILITY OF NOT EXCEEDING LEVEL
50
-70
-65
-60
-55
-50
-45
-40
-35
ACCELERATION LEVEL, dB (re. 1g)

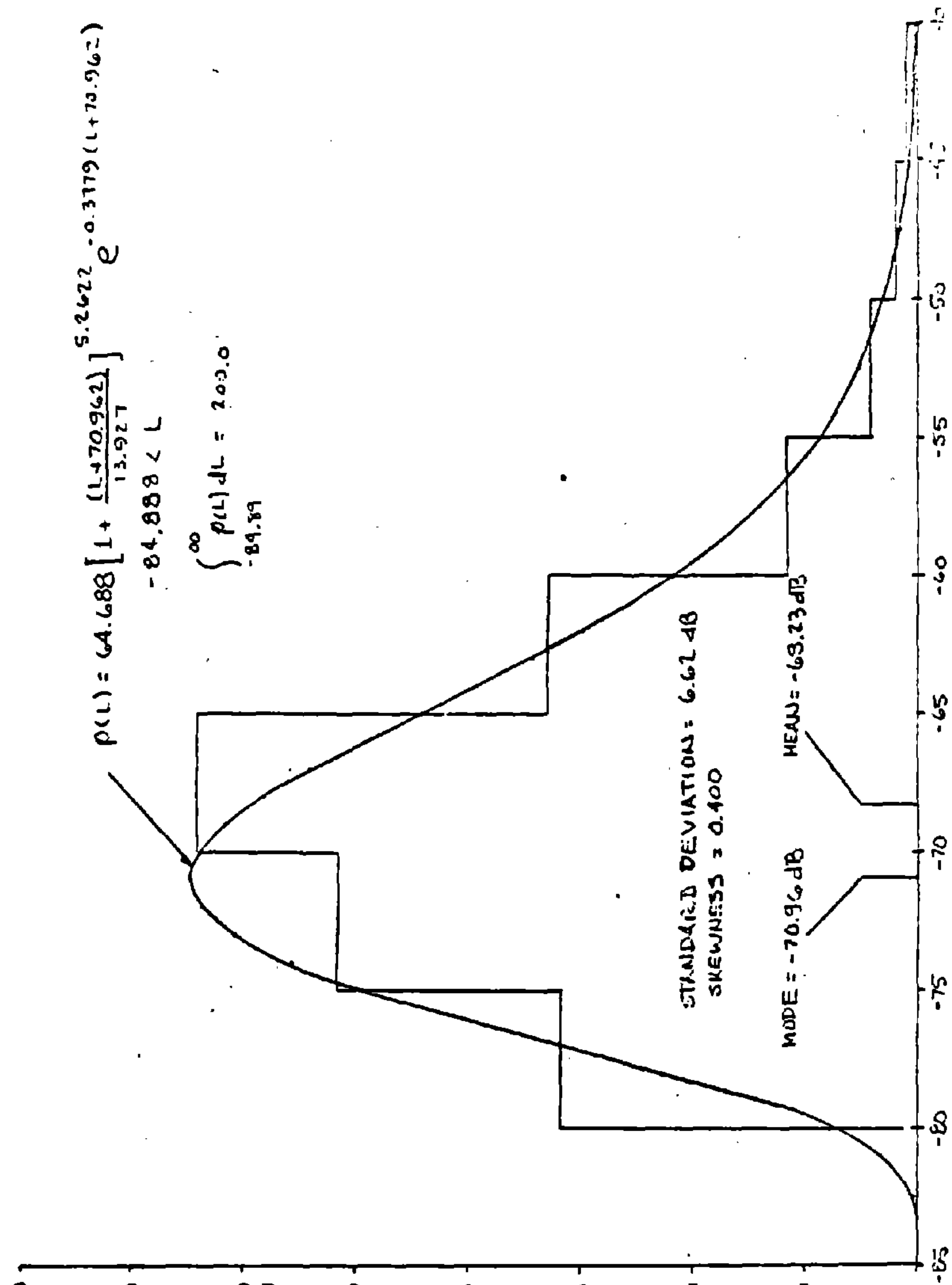


MEAN LEVEL = -55.64 dB
MODE LEVEL = -58.49 dB
STANDARD DEVIATION = 7.71 dB
SKEWNESS = 0.3696
p(L) = 4.543[1 + (L+59.49)/11.957]^0.783 [1 - (L+59.49)/24.439]^1.600
-70.45 < L < -34.05
PERCENTAGE OF OBSERVATIONS
20
10
MODE
MEAN
-70
-65
-60
-55
-50
-45
-40
-35
ACCELERATION LEVEL, dB (re. 1g)



-84.53 < L
p(L) = 71.278[1 + (L+71.45)/13.078]^5.623 e^-0.4303(L+71.45)
∫ p(L)dL = 200.00
STANDARD DEVIATION = 5.93 dB
SKEWNESS = 0.383
MODE = -71.45dB
MEAN = -69.13dB
-85
-80
-75
-70
-65
-60
-55
-50
-45
80
70
60
50
40
30
20
10


p(L) = 67.512[1 + (L+70.06)/13.893]^5.6304 e^-0.4076(L+70.06)
∫ -83.95 to ∞ p(L)dL = 200.00
STANDARD DEVIATION = 6.32 dB
SKEWNESS = 0.1915
MODE = -70.06 dB
MEAN = -68.85
70
60
50
40
30
20
10
-85
-80
-75
-70
-65
-60
-55
-50
-45
-40



p(L) = 64.688[1 + (L+70.962)/13.927]^5.2622 e^-0.3779(L+70.962)
-84.888 < L
∫ p(L) dL = 200.0
-84.89 ∞
STANDARD DEVIATION = 6.62 dB
SKEWNESS = 0.400
MEAN = -63.23 dB
MODE = -70.96 dB
0
10
20
30
40
50
60
70
80
-85
-80
-75
-70
-65
-60
-55
-50

Serial No.	Event No.	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5		Channel 6	
		L_p	$\overline{L}_{rms}$	L_p	$\overline{L}_{rms}$	L_p	$\overline{L}_{rms}$	L_p	$\overline{L}_{rms}$	L_p	$\overline{L}_{rms}$	L_p	$\overline{L}_{rms}$
18	39	-48.0	-59.4	-43.1	-58.6	-48.0	-60.4	-43.1	-56.8	-48.0	-61.1	-38.4	-52.7
19	40	-48.0	-62.3	-46.0	-63.5	-50.5	-67.3	-48.0	-62.6	-48.0	-66.7	-39.2	-56.6
20	41	-54.0	-69.9	-54.0	-71.7	-60.0	-74.0	-54.0	-69.1	-60.0	-72.4	-50.5	-65.8
21	44	-48.0	-59.7	-40.0	-58.0	-50.5	-62.3	-40.0	-56.8	-44.4	-60.6	-37.1	-49.8
17	36	-54.0	-69.1	-54.0	-68.6	-60.0	-71.1	-50.5	-67.1	-54.0	-70.2	-48.0	-63.6
22	46	-54.0	-67.5	-50.5	-66.6	-60.0	-71.1	-54.0	-65.4	-54.0	-69.4	-46.0	-61.3
24	70	-37.1	-52.7	-46.0	-60.3	-40.0	-54.9	-36.5	-51.8	-43.1	-57.9	-40.9	-56.1
27	44	-41.9	-56.8	-46.0	-61.2	-50.5	-62.2	-48.0	-62.7	-48.0	-64.4	-54.0	-65.4
25	82	-44.4	-58.1	-48.0	-62.3	-50.5	-63.9	-50.5	-62.6	-50.5	-63.2	-48.0	-60.6
28	95	-37.1	-55.2	-43.1	-59.3	-50.5	-65.2	-54.0	-66.7	-50.5	-64.9	-54.0	-65.8
12	139	-40.0	-54.9	-43.1	-57.1	-43.1	-58.1	-44.4	-58.6	-46.0	-62.0	-50.5	-62.7
13	140	-40.9	-55.5	-40.9	-57.0	-46.0	-60.4	-46.0	-60.2	-48.0	-63.9	-50.5	-64.4
14	141	-37.1	-52.5	-37.1	-53.5	-43.1	-56.5	-43.1	-56.3	-48.0	-61.4	-46.0	-60.3
15	142	-43.1	-58.3	-43.1	-58.8	-48.0	-63.1	-48.0	-62.6	-48.0	-65.5	-54.0	-66.9
29	105	-48.0	-63.1	-50.5	-66.2	-48.0	-63.6	-35.4	-49.3	-54.0	-66.4	-37.1	-53.4
31	109	-46.0	-60.2	-54.0	-65.8	-48.0	-60.6	-30.8	-42.6	-50.5	-63.6	-35.4	-51.4
32	112	-48.0	-63.0	-50.5	-65.5	-40.9	-57.0	-24.4	-39.8	-48.0	-63.7	-29.4	-44.5
4	120	-43.1	-56.1	-50.5	-63.1	-50.5	-62.3	-32.4	-47.4	-48.0	-60.3	-26.0	-40.7
3	118	-50.5	-66.6	-54.0	-68.2	-46.0	-61.7	-29.1	-44.7	-54.0	-68.2	-25.4	-40.6
5	121	-44.4	-58.7	-54.0	-66.2	-48.0	-60.8	-35.9	-48.1	-50.5	-62.3	-29.1	-41.9
7	124	-50.5	-62.5	-44.4	-58.6	-48.0	-60.6	-46.0	-58.8	-35.4	-50.6	-46.0	-59.5
8	129	-46.0	-59.9	-38.4	-56.2	-48.0	-60.0	-41.9	-57.6	-36.5	-53.6	-46.0	-58.9
9	130	-40.9	-53.0	-40.9	-51.9	-33.2	-51.9	-41.9	-53.3	-37.7	-49.7	-41.9	-53.8
10	133	-50.5	-62.7	-50.5	-62.4	-48.0	-60.3	-43.1	-54.8	-41.9	-57.0	-35.4	-48.0

APPENDIX VI

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