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State-Of-The-Art Review Prediction and Control of Groundborne Noise and Vibration From Rail Transit Trains

Annotated Bibliography

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Interim Report

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16. Abstract

This annotated bibliography has been compiled as part of a comprehensive review of the literature pertaining to groundborne noise and vibration created by rail transit operations. Included are over 300 references, most with annotations. The selected references include published articles and books from the standard literature, in addition to many unpublished references. The unpublished references are of particular interest since it is these reports that often contain the most current information about the techniques that are being used by transit systems to control groundborne noise and vibration, and the practical problems that may have developed when the methods were implemented.

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PREFACE

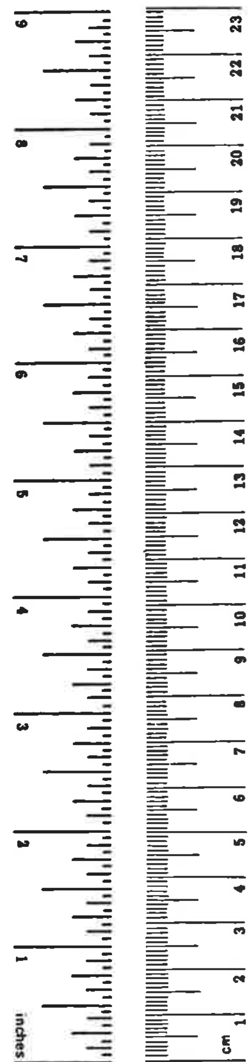
This interim report presents the annotated bibliography of a comprehensive review of the state-of-the-art in the prediction and control of groundborne noise and vibration. A companion report presents the state-of-the-art review. This report has been prepared by Wilson, Ihrig & Associates, Inc. (WIA) under contract to the U.S. Department of Transportation (contract DOT-TSC-1796). The project was managed by the Transportation Systems Center (TSC), The work was performed by James T. Nelson, Hugh J. Saurenman, and Thomas Mugglestone of WIA with significant contributions by George Paul Wilson of WIA and S. W. Nowicki of London Transport International. The assistance of Michael Dinning, the TSC Technical Monitor, and the suggestions and comments of the American Public Transit Association Urban Rail Noise Abatement Liaison Board are also gratefully acknowledged.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

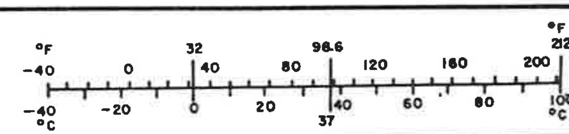
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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. INTRODUCTION

Following is a comprehensive bibliography of references that are related to the prediction and control of groundborne noise and vibration created by rail rapid transit systems. This information has been compiled as part of an extensive review of the existing state-of-the-art. One factor that became evident as the review progressed is that there has been a tremendous amount of research and development effort related to predicting and controlling groundborne noise and vibration. This research has been carried out by many different transit systems, governmental bodies, and consulting firms in Europe, Japan, and the United States. However, we are not aware of any previous effort to perform a comprehensive review of the existing state-of-the-art in this field.

For this bibliography, an effort has been made to review as many references as possible that are related to groundborne noise and vibration. The references selected include published articles and books from the standard literature in addition to many unpublished references. The unpublished references are of particular interest. They primarily consist of reports prepared by consultants for transit systems and unpublished papers presented at professional society meetings. Typically, these reports contain the most current information about the techniques that are being used by transit systems to control groundborne noise and vibration and the practical problems that may have developed when the methods were implemented.

The bibliography is divided into three parts. Part A includes all references that are related to rail transit groundborne noise and vibration. Over 200 references with 180 annotations are included. The second section, Part B, includes references that are related to building and/or ground vibration but are not specifically related to rail transit. For example, references on traffic-induced building vibration are included in this section. The final section, Part C, contains papers that are not specifically related to transit, building vibration, or ground vibration, but which may have application to the prediction and control of groundborne noise and vibration. Most of the references in Part C relate to analytical techniques or theoretical models that could have applicability to groundborne noise and vibration.

The references are not placed in any specific order. However, a subject index, an author index, and a measurement data index have all been provided to aid the user in locating the references of interest. Using one or more of these indices should allow the user to rapidly locate references of interest.

Although this bibliography contains over 300 references, it should be recognized that with the large amount of continuing research, it is impossible to include all relevant references. However, the format that has been chosen for the bibliography allows it to be continuously updated without modifying the existing text and numbers. Only the indices will need to be modified.

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5. ANNOTATED BIBLIOGRAPHY

PART A: REFERENCES RELATED TO RAIL TRANSIT GROUNDBORNE NOISE AND VIBRATION

A-001 Kurzweil, L.G.
Groundborne noise and vibration from underground rail systems.
(journal article) J Sound Vibr, 66:3,363-370 (1979).

The general problem of groundborne vibration from transit systems is presented. The simple procedure developed by J. Lange for estimating A-weighted noise in buildings is presented. Parametric effects are considered, including effects of noise control provisions, train speed and load, fastener stiffness, and propagation distance. The coupling loss for vibration transmitting from the soil to the building and conversion to noise levels is discussed. The article is a summary of the literature and provides a solid introduction to the nature of groundborne noise.

A-002 Ungar, E.E.; Bender, E.K.
Vibrations produced in buildings by passage of subway trains; parameter estimation for preliminary design.
(conference paper) in: Proceedings of Internoise 75 pp 491-498. Tohoku University, Sendai, Japan (1975).

This paper concerns vibration annoyance criteria, subway tunnel vibration, propagation of vibration through the ground, the effects of intervening interfaces and soil layering and vibration attenuation in buildings. The effects of tunnel track and vehicle parameters including the founding conditions of the soil around the tunnel, rail fastener thickness, track roughness and joints, vehicle speed, and unsprung vehicle weight are also addressed. Techniques are presented for predicting groundborne vibration in buildings when only a limited amount of information on the various parameters is available.

The loss factors associated with shear and compression waves are assumed approximately equal. Because shear waves have considerably lower propagation velocities, the result of this assumption is that shear waves are assumed to attenuate much more rapidly than compression waves. Thus, the compression wave is considered to be the only wave motion of interest. No discussion of Rayleigh waves or other wave forms nor of the partition of energy between shear, compression, or Rayleigh waves, is included. A relatively detailed table of soil and rock properties is presented which includes the wave speed of longitudinal and transverse waves, density, and loss factors for various soils and rocks.

A-003 Wilson, G.P.
Noise and Vibration Characteristics of High Speed Transit Vehicles.
(technical report) Wilson, Ihrig & Associates, Oakland, CA.
for: U.S. DOT; Office of Noise Abatement, DOT-OS-A9-032.
avail: U.S. National Technical Information Service, OST-ONA-71-7 (1971).

A general discussion of groundborne noise and vibration from rapid transit vehicles is presented. Topics include vibration transmission in soil and rock, geological effects, groundborne noise in buildings, and effects of vibration of foundations and structures. A particularly interesting discussion of subway structure interaction with soil and rock is included, using the concept of mechanical impedance and a lumped single-degree-of-freedom model of the tunnel, and soil stiffness.

A-004 Tokita, Y.; Oda, A.; Shimizu, K.; Kimura, K.
On the groundborne noise propagation from a subway.
(conference paper) presented at joint meeting of the Acoustical Societies of America and Japan, Honolulu, HI (1978).

Presented are models for vibration radiation from subway tunnels and propagation through soil layers, and supporting experimental data. The assumptions used in formulating the model are:

- The source is equivalent to an imaginary incoherent line source located below the subway structure.

- Attentuation of vibration is caused in part by barrier effects produced by the subway structure interrupting the propagation path from the imaginary line source.

- Effects of soil layering and the angle of incidence at the soil layer interface affect vibration transmission.

The prediction of level as a function of distance is in terms of overall vibration acceleration which is effectively determined by the 50 and 60 Hz 1/3 octave bands. The attenuation model includes soil parameters such as density, vibration propagation velocity, and damping factor. These parameters are related to so-called "N values of hardness," and are grouped in terms of "soft," "rather hard," and "hard." Correction factors are given for train speed and radius of track curvature.

At the ground surface, the vibration level appears to initially decrease with increasing distance from track centerline, thereafter increasing with distance from the subway structure until a maximum is reached at about 30 meters from the track centerline. For deep tunnels the second maximum is located at a greater horizontal distance from the track than for shallower tunnels.

Finally, a discussion of interior building noise level as a function of ground vibration level is presented. However, the prediction procedure relies on the so-called source intensity of the imaginary line source beneath the tunnel. This quantity is, of course, unknown and very difficult and probably impossible to be measured.

A-005 Wilson, G.P.
Groundborne Vibration Levels from Rock- and Earth-Based Subways.
(report) Wilson, Ihrig & Associates, Oakland, CA.
for: De Leuw, Cather & Company, Washington, DC (1971).

Based on measurements performed at the Toronto Transit Commission (TTC) system, techniques were developed for estimating octave band groundborne noise and vibration from rapid transit systems. These basic techniques have been used for predicting groundborne noise and vibration in buildings at numerous transit systems other than just WMATA Metro and are essentially similar to the methods outlined in Reference A-003.

A-006 Verhas, H.P.
Prediction of the propagation of train-induced ground vibration.
(journal article) J Sound Vibr, 66:3,371-377 (1979).

The theoretical and experimental aspects of the attenuation of groundborne vibration with distance are considered. The theoretical discussion is very basic but refers to line and point sources, shear, compression, and Rayleigh waves, and damping factors. Experimental data describing the level difference between two measurement points as a function of frequency are presented, and data are also presented for mainline rail operations on at-grade ballast and tie trackbed. Three models for prediction of the propagation of train-induced ground vibration are presented. They are:

- Line source
- Point source
- Superposed line and point source.

The experimental data are from measurements at Hathern and Blisworth in Britain, and are well documented in other previous publications. These data are compared in detail with predictions based upon the three models, attempting to correlate, in the case of the superposed models, assumed values of energy partition between point and line sources and between body and surface waves with observed ground vibration level differences. When linear acceleration levels are considered, a line source model with body wave propagation is found to give good predictions. However, when spectra are considered, damping must be included. The damping should be taken proportional to exp(-nN), where "n" is a representative frequency-independent loss factor for the soil, and "N" is the distance from the source in wavelengths. The superposed model is found to give good predictions, if the vibration energy partition is assumed to be a function of soil characteristics.

A-007 Wolfe, S.L.
Groundborne Vibration from 2000, 2200 and 2400 Series CTA Transit Trains.

(preliminary report) Wilson, Ihrig & Associates, Oakland, CA. for: Chicago Transit Authority, Chicago, IL (1978).

This is a letter report on measurements of groundborne vibration with several different types of CTA transit cars. The results show substantial differences in groundborne vibration levels and indicate that a significant reduction of vibration can be achieved by modifying the bogie design. It appears that the primary suspension stiffness of the bogie is the most important factor. Maintaining the resonance of the primary stiffness below about 8 Hz results in the lowest levels of groundborne noise and vibration.

A-008 Johnson, L.; Gilchrist, A.; Healy, M.; Bush, C.; Sheldon, G.
Truck Design Optimization Project Phase II: Analytical Tool Assessment Report.
(technical report) Wyle Laboratories, Colorado Springs, CO. for: U.S. DOT; Federal Railroad Administration, FRA-OR&D-79-36 (1979).

Various computer programs for modeling lateral stability, curve negotiation, ride quality, and trackability of railway vehicles are summarized. All of the programs use multi-degree-of-freedom models. Most of the programs are for nonlinear modeling of vehicle components and for modeling of large-scale motions. However, a number of the programs may be applicable to the evaluation of the effect of the truck dynamics on groundborne noise and vibration. The programs which appear to be most applicable are DYNALIST II, HALF, FLEX, AND LATERAL. Most or all of these programs have been implemented on the TSC DEC System 10 computer.

A-009 Saurenman, H.J.; Shipley, R.L.; Wilson, G.P.
In-Service Performance and Costs of Methods to Control Urban

Rail System Noise: Final Report.
(final report) Wilson, Ihrig & Associates, Oakland, CA and De Leuw, Cather & Company, Washington, DC,
DOT-TSC-UMTA-79-43.
for: U.S. DOT; Transportation Systems Center, Cambridge, MA,
UMTA-MA-06-0099-80-1 (1979).

Included in this report are results of measurements of groundborne vibration on the SEPTA system with trains using standard solid steel and resilient wheels, and running on ground and unground rail. The measurement results show significant reduction of groundborne vibration above 20 Hz with resilient wheels. In addition, measurable reduction of vibration level was observed with both standard and resilient wheels after wheel truing, while only marginal reduction resulted from rail grinding. Before the rail was ground there was no evidence of corrugation or extensive pitting or spalling.

A-010 Anonymous
Paris Metro Internal Data.
(data report) Paris Metro, (1970) [unpublished].

Data from the Paris Metro System indicates that rubber tire systems create substantially less groundborne vibration than steel wheel trucks. The levels are comparable to levels produced by rail transit vehicles operating on floating slab track.

A-011 Paolillo, A.W.
Groundborne Vibration Generated by Rapid Transit Rail Cars.
(report) New York City Transit Authority, Engineering Department (1978).

Vibration problems associated with the design of rail vehicle suspension systems are reviewed. Groundborne vibration was found to exhibit a strong spectral component at about 20 Hz. This 20 Hz component is identified with a calculated primary truck resonance frequency of 21 Hz for the NYCTA R-46 transit vehicles. This is in contrast to the trucks of earlier vintage R-32 cars whose primary resonance frequency was calculated to be 7 Hz. The R-46 cars use Rockwell trucks with rubber journal bushings for the primary suspension. Also, "over-stressing and cracking and other problems" of the Rockwell truck frame are noted. As a result, Rockwell has developed a retrofit modification for the Rockwell truck using coil springs in place of rubber bushings. Tests indicate that the coil springs reduce the primary resonance frequency and dynamic stresses in the truck casting. Additional comments indicate that the impedance of the wheel (looking up from the rail) is mass-like above the resonance frequency of the primary suspension.

Vibration measurement results reported by NYCTA indicate that the NYCTA floating slabs with a 16 Hz resonance frequency amplify the 20 Hz component of vibration associated with the Rockwell truck. Additional resonances near 20 Hz for building structures apparently contribute to the disturbance of the building occupants. Data are presented in 1/3 octave band levels over the frequency range of 3.15 Hz to 160 Hz and also in a constant bandwidth analysis plotted on a "Log frequency" scale.

A-012 Wilson, G.P.
Noise Levels from Operation of CTA Rail Transit Trains. (report) Wilson, Ihrig & Associates, Oakland, CA. for: City of Chicago, Chicago Transit Authority (1977).

Noise measurement data for at-grade ballast and tie, aerial structure, and subway configurations are presented. The relevance to groundborne vibration concerns the effect of vehicle bogie modifications on noise and the possible interference of a similar reduction of ground loading. In particular, the lowest wayside A-weighted levels were achieved with the use of modified bogies with soft axle journal sleeves; typically the levels were 3 to 6 dBA lower than for the standard bogies.

A-013 Wilson, G.P.
Analysis and Recommendations - Resiliently Mounted Track Slabs for the Washington METRO.
(report) Wilson, Ihrig & Associates, Oakland, CA. for: De Leuw, Cather & Company, Washington, DC (1970).

Design considerations for the floating slab track isolation systems used on the WMATA system are presented. The relative merits of fiberglass load bearing pads and natural rubber, neoprene, and synthetic rubber pads are compared. Air stiffness is noted to have a significant effect on the floating slab resonance frequency, the air stiffness being comparable in magnitude to the stiffness provided by the resilient support pads. Presented are:

- General criteria for determining the need for floating slab trackbeds.

- Estimates of vibration levels from Metro system operations, including evaluations of the effects of various factors on vibration propagation and radiation from subway structures.

- Estimates of the vibration levels which will be transmitted to buildings.

The expected acceleration levels 25 feet from a Metro system tunnel and the attenuation of vibration as a function of distance from the subway structure are given in terms of octave band levels which are based on measurements performed at the TTC (Toronto) and BART (San Francisco) systems. Also given is the approximate coupling loss expected for heavy masonry buildings supported on piles.

A-014 Toronto Transit Commission
TTC Track Vibration Isolation System.
(report) Toronto Transit Commission, Engineering Department (1978).

The vibration reduction achieved with the use of the discontinuous double-tie floating slab system used on the TTC subways is discussed. Both MURLA (Melbourne) and MARTA (Atlanta) have used similar floating slab systems. One-third octave band acceleration spectra are presented for vibration levels at 50 feet, 100 feet, and 200 feet from the subway structures with and without the double-tie floating slab systems. The vibration reduction achieved with the use of the double ties is typically about 15 to 20 dB above 20 Hz.

A-015 Lawrence, S.T.
Toronto's double-tie trackbed system.
(conference paper) presented at American Public Transit Association Rapid Transit Conference, Chicago, IL(1978).

This paper is a detailed discussion of the vibration reduction achieved with the use of the double-tie trackbed used on the Toronto Transit Commission subways. One-third octave band vibration acceleration spectra are presented for subway structures with and without double-tie floating slab systems. Measurement locations were on the invert bench or side bench of the subway, various locations at the ground surface, and in side buildings near the subway. Also presented are plots of vibration level as a function of train speed. Other information presented concerns contract document preparation, and manufacturing and installation costs. Numerous photographs are included.

A-016 Corbin, J.C.
Statistical Representation of Track Geometry. Vol 1: Main Text.
(draft final report) ENSCO, Inc., Springfield, VA., ENSCO-1112. for: U.S. DOT; Research and Special Programs Administration, DOT-TSC-1211 (1979).

A model for track geometry variation is presented. There is little if any data concerning rail roughness within the range of wavelengths applicable to groundborne noise and vibration.

A-017 Anonymous
Development of a Sound Dampened, No Ballast Rail Structure with Elastic Bearing Cross-Ties.
(technical report) extracted from an article on the Voest Resilient Tie, from a Vienna U-Bahn Technical Report, included in Toronto Transit Commission report RD-115 (1976) [transl by Reuscher, H.].

Presented is a summary of design considerations and results of vibration measurements for ballast and tie trackbeds, plastic and wooden ties, fastener isolation material such as rubber or wood and Isolif-Triplex ballast mats. The measurements were carried out by Professor Bruckmayer of the Institute for Heat and Sound Technology and Dr. Judith Lang. Most of the vibration data are given in terms of overall vibration velocity or A-weighted vibration velocity. Ballast mats gave some of the greatest reduction of overall vibration velocity in the frequency range of 63 to 500 Hz. No spectra are presented.

A-018 Bender, E.K.; Kurze, U.J.; Nayak, P.R.; Ungar, E.E.
Effects of Rail Fastener Stiffness on Vibration Transmitted to Buildings Adjacent to Subways.
(report) Bolt, Beranek & Newman, Inc., Cambridge, MA, BBN-1832. for: Washington Metropolitan Area Transportation Authority (1969).

A theoretical analysis of the effect of rail fastener stiffness on forces transmitted to the invert is presented. Specific topics include the representation of wheel and rail roughness, vehicle impedance, rail impedance, and applied forces. The analysis indicates that the magnitude of the integrated net force transmitted to the invert is equivalent to that which would be transmitted through a single-degree-of-freedom vibration isolation system. A simple formula is presented for the prediction of fastener performance as a function of frequency over the range of 20 to 300 Hz. Assuming a 30,000 lb point static load, the maximum rail stress, maximum rail deflection, and vibration isolation relative to the standard Toronto fastener (stiffness equals 4,300 lb/in^2) are given for fastener stiffness from 275 to 3,200 lb/in^2.

At frequencies above about 50 to 60 Hz, the reduction of vibration transmission in decibels varies as 20 log K where K is the fastener stiffness. Below 30 Hz, amplification of rail forces is considered possible.

The report contains a summary of practical design considerations for rail fasteners. Specific topics include fastener design, resilient pads with variable spring rates, the location of the resilient pads, and a brief comparison of rail fasteners and resiliently supported ties. The report concludes by recommending an equivalent fastener stiffness of approximately 800 lb/in. per lineal inch of rail. This relatively low stiffness must be contrasted with the normally accepted fastener stiffness of at least 3,000 lb/in./in. used on most transit systems. The recommendation of 800 lb/in./in. is apparently motivated by acoustical considerations without regard to track deflection requirements or other safety considerations.

A-019 Manning, J.E.; Hyland, D.C.; Tocci, G.
Vibration Prediction Model for Floating Slab Rail Transit Track.
(final report) Cambridge Collaborative, Inc., Cambridge, MA.
for: U.S. DOT; Transportation Systems Center,
UMTA-MA-06-0025-75-13 (1975).

A detailed analytical model of distributed floating slab and rail systems is described together with supporting measurement data. The basic conclusion of this study is that the use of a single-degree-of-freedom model for a floating slab is reasonable for evaluation of most design considerations. The analytical model is extended to the case of discontinuous floating slabs or "floating ties" by setting of slab bending stiffness to zero. The model presented in this report appears to be too complex to be a practical design tool, particularly since computer programs simulating the model have not been developed.

A-020 Wilson, G.P.
Diablo Test Track Noise and Vibration Measurements.
(technical report) Wilson, Ihrig & Associates, Oakland, CA.
for: Parsons-Brinckerhoff-Tudor-Bechtel, San Francisco, CA
(1967).

Measurements were conducted on the BART system to evaluate the noise and vibration reduction of various wheel and fastener designs. The ground surface vibration was measured at various distances from aerial structure and ballast and tie track. The fasteners tested included the:

- Toronto fastener
- Pandrol fastener with 3/16 in. pad
- Pandrol fastener with 1/8 in. pad and nylon clips
- General Tire fastener
- B. F. Goodrich fastener.

Measurements were performed with the prototype cars fitted with SAB resilient wheels, BLH resilient wheels, and aluminum centered steel wheels.

A-021 Anonymous
Structureborne Noise Measurements at the S-Bahn in Frankfurt/M.
(research report) Technical University of Munich, Institute of Rural Route Construction, Munich, Germany, # 566
(1972) [in German].

Measurements of tunnel wall vibration at adjacent sections of tunnel, one with ballast and tie track and the other with resiliently supported ties, were performed at the S-Bahn in Frankfurt. One-third octave band spectra are given for the frequency range of 25 to 160 Hz. Vibration levels of 20 to 30 dB relative to the ballast and tie case are reported for the resiliently supported tie in the frequency range of 50 to 80 Hz.

A-022 Anonymous
Structureborne Noise Measurements at the S-Bahn in Munich. (research report) Technical University of Munich, Institute of Rural Route Construction, Munich, Germany, # 520 (1971) [in German].

Vibration measurements on subway walls and floors for both ballast and tie and resiliently supported concrete ties were performed at the S-Bahn in Munich, Germany. One-third octave band data are presented over the frequency range of 25 to 160 Hz. The effects of train speed, tunnel floor versus tunnel wall vibration, and ballast and tie versus resiliently supported unbraced precast ties and resiliently supported "mutually braced" precast ties are evaluated.

A-023 Koch, H.W.
Structureborne Noise Levels of Superstructure Traveled Upon for Several Years and of Altered Superstructure with Broken Rocks.
(private communication) (date uncertain)
[in German].

Comparisons are drawn between vibration levels for the rail flange, "raft" foundation, wall, and ceiling. The discussion encompasses ballast trackbeds with sublayers of concrete, dense sand, and additional ballast. Although no spectra are presented, 1/3 octave band peaks are apparently in the range of 50 to 63 Hz. A particularly noteworthy result of this report is that a doubling of tunnel wall thickness from 40 cm to 80 cm produced an 18 dB reduction of overall wall vibration velocity level.

A-024 Oelkers, H.D.; Koch, H.W.
Results of noise measurements for different types of superstructure existing in urban traffic.
(journal article) VDI - Berichte, no. 170 (1971) [in German].

Measurements are summarized and compared for groundborne noise and vibration at five subway systems in Europe, including Hamburg-Horner-Rennbahn, Hamburg-"Hagenbeek," Milan, Rotterdam, and Cologne. Vibration reductions relative to standard ballast and tie trackbeds are presented for:

- resilient fasteners
- different invert designs
- rigid fasteners with a poplar wood intermediate layer
- cushioned and uncushioned ground plates
- shorted and unshorted resiliently supported slabs.

Additionally, data for rubber ballast mats as used in Paris are presented, indicating significant vibration reduction with ballast mats.

Vibration levels for resilient and rigid wheels used on the Milan system are presented. The resilient wheels created higher vibration levels at low frequencies. The data are presented in terms of 1/3 octave band spectra from 25 Hz to 315 Hz, although some data extend down to 8 Hz. Note that drawings of each of the rail support configurations are presented.

A-025 Lang, J.
Structureborne Sound Level in Subway Tunnels.
(report) Physico-Technical Research Institute for Heat and Sound Technology, #3811/WS (1977)
[in German]

Vibration measurements were performed on the transverse bench and steel tunnel wall of a subway tunnel. One-third octave band spectra from 5 to 325 Hz are included for the vertical, longitudinal, and transverse directions on the bench and on the tunnel wall. Train passbys of 40, 60, and 70 km/hr as well as a train braking from 70 km/hr were measured. The 1/3 octave band data show a variation of less than 5 dB over the speed range given. Larger variations are observed between the three vibration measurement axes. Levels of perpendicular wall vibration are about 10 dB higher than vertical or horizontal vibration levels at the transverse bench.

A-026 Hauck, G.; Willenbrink, L.; Stuben, C.
Koerperschall- und Luftschallmesungen an unterirdischen Schienenbahnen. (...noise measurements at underground rail transit systems).
(journal article) Eisenbahntechnische Rundschau, heft 7/8 (1972) [in German].

Measurement results for noise and vibration in subways, transit vehicles, and nearby buildings are presented. One-third octave band spectra are presented for frequencies above 20 Hz. Comparisons are made of noise and vibration levels with trains operating on floating slabs and on ballast and tie trackbeds. Also given are car interior noise levels at-grade and inside subways and on both ballast and tie and floating slab trackbeds in subways.

A-027 Volberg, G.
Structureborne Noise Level Measurements In and Around the U-Bahns.
(private communication) (date & source uncertain)
[in German].

Subway structure vibration for different configurations of track support systems on the Nurnberg system are discussed. One of these is standard ballast and tie, while the remaining four are designs with resilient elements placed between the rail and the tie and between the tie and invert. Tests were conducted at 20, 40, and 60 km/hr with measurements taken on the rail, invert, and tunnel wall and ceiling. One-third octave data are presented for frequencies above 25 Hz. Additional data for resilient mats placed within the ballast on another trackbed construction are vague. Measurements of attenuation of groundborne vibration as a function of frequency and distance from the subway are also presented.

A-028 Colombaud, J.L.
Noise and vibration levels suit ballastless track for underground railways.
(journal article) Rail Eng Intl, 3:5,235-240 (1973).

Noise and vibration levels measured on the Paris RER with R.A.T.P., SNCF (Type F), and RS-STEDEF rail support systems are compared with levels for ballast and tie trackbed. The RS-STEDEF System gave the best overall performance and, when combined with a thin layer of ballast as sound absorption treatment, noise levels in the tunnel and vehicles were comparable with those obtained with the conventional ballast and tie configuration. A high degree of internal damping ascribed to the RS-STEDEF resilient element is claimed to be responsible for the relatively low 63 Hz octave band vibration level achieved in comparison with other fastener designs. Octave band data are presented from 31.5 to 1000 Hz.

A-029 Lang, J.
Messergebnisse um Koerperschallschutz fuer U-Bahnen.

(Measurement results seen in relation to protection from structureborne noise in subways).
(conference paper) in: Proceedings of 7th International Congress on Acoustics. pp 421-424 Akademia Kiado, Budapest, Hungary, (1971) [in German].

A-weighted noise and impact vibration velocity measurements performed on the Vienna system are discussed. A-weighted noise levels of 42 to 54 dBA are reported in buildings over and adjacent to the subway. Other observations indicate that noise levels increase with train speed, and are dependent on the type of vehicle and roadbed. Roadbed configurations tested with an impact device were:

- Wood ties on concrete base
- Wood ties on 20 cm and 40 cm ballast
- Wood ties on rubber pads on concrete
- Wood ties on ballasted floating slab
- Wood ties on ballast with Isolif-Triplex ballast mat
- Wood ties on ballast on a "bed of rubber pieces".

The ballast and tie track with ISOLIF ballast mat gave about 15 dB reduction of "impact sound" at the invert.

Also presented are measurements of A-weighted noise levels in building cellars and ground floor rooms near several subway sytems. These data are cited in the literature and form the basis of the simple prediction method of Reference A-1.

A-030 Hofer, J.; Sailler, J.
Versuche fuer einen schotterlosen Oberbau mit elastisch gelagerten Querschwellen. (Ballastless superstructure with elastic layered cross-ties)
(journal article) Verkehr und Technik, 8,381-383 (1972) [in German].

Presented is a discussion of a ballast-free trackbed designed for the Vienna Stadtbahn and U-Bahn using polyurethane plastic ties, ribbed rubber sheathing, and fiberglass sheets. Overall noise and vibration data are discussed, but no spectra are presented. These components were eventually decided upon for future installation on the Vienna U-Bahn. It is noted that ballast has the advantage of being sound absorptive, however, that same absorption could be achieved with auxiliary treatment in areas of ballastless track. The ballastless track is considered very desirable from a long-term economic point of view.

A-031 Wright, A.T.
Evaluation of Increased Mass for Floating Slabs.
(letter report) Wilson, Ihrig & Associates, Oakland, CA.
for: Metropolitan Atlanta Rapid Transit Authority (1979).

The change of 1/3 octave band vibration level spectra achieved by doubling the mass of a line of discontinuous floating slabs is discussed. The extra mass is estimated to reduce the resonance frequency from 18 Hz to 14 Hz when there is no load and from 16 to 11.5 Hz when a train is on the slab.

Reducing the resonance frequency of the floating slab was found to reduce the groundborne vibration in nearby buildings. Vibration was reduced by destroying coincidence between structure resonances, the slab resonance, and the resonance of the primary suspension system, all of which were close to 16 Hz with the original configuration.

A similar problem with low-frequency vibration is outlined by Paolillo in Reference A-011. He concludes that the primary stiffness resonance frequency of the Rockwell Truck is the source of the problem at NYCTA. The MARTA vehicles use the same basic type of truck as the NYCTA R-46 cars.

A-032 Millbom, B.
Reduction of Noise and Vibration in Tunnels; Report from Tests in Stockholm.
(private communication) (date & source uncertain) [in Swedish].

Four types of trackbed are described, including: (1) Ordinary ballast of standard design; (2) Ordinary ballast on a bed of three layers of 5 cm mineral wool sheets; (3) Track directly on a sandwich plate supported by rubber pads; and (4) Normal ballast in a concrete box supported by rubber pads. Triaxial vibration velocity data are presented for measurements on the wall and ceiling of the subway structure and on a rock surface above the subway. However, the data have apparently been A-weighted, and no spectra are available. The configuration with ordinary ballast on a bed of three layers of 5 cm mineral wool sheets was selected as giving the best performance at least cost, with the added advantage of rapid installation.

A-033 Wilson, G.P.; Knight, K.G.
Design and performance of a floating slab trackbed.
(conference paper) in: Noise-Con 73 Proceedings, pp 146-151, Institute of Noise Control Engineering, Poughkeepsie, NY (1973).

The design and test results for the floating slab vibration isolation system used on the WMATA Metro system is discussed. Design resonance frequencies were 25 Hz for rubber support pads and 16 Hz for fiberglass support pads. Field tests of a prototype floating slab indicated higher resonance frequencies, apparently due to the perimeter isolation board being stiffer than anticipated. Damping ratios were found to be 0.16 and 0.18 for the rubber pad and fiberglass pad designs, respectively. Generally, 10 to 20 dB of vibration isolation was achieved in the range of 31.5 Hz to 500 Hz. The natural rubber pad system appeared to perform slightly better than the fiberglass pad system.

A-034 Tajima, H.; Kiura, K.
Laying of track ballast mats in Shinkansen.
(journal article) Permanent Way, 15:3,11-19 (1974).

Use of ballast mats to reduce pulverization, hardening, and maintenance of ballast, as well as noise and vibration is discussed. Apparently, about 8 dB reduction of noise beneath the Shinkansen line aerial structure was achieved, together with about 20% to 30% reduction of vibration acceleration. No spectra are presented. The reduction of maintenance time with ballast mats was about 50%. Also, ballast mats can be easily installed during the course of normal ballast renewal. The mats were manufactured from discarded rubber tires.

A-035 Steinbeisser, L.
Koerperschallmessungen in Zurich und Munich. (Acoustic body conduction measurements).
(journal article) VDI - Berichte, No.217, pp 37-42 (1974) [in German].

Measurements of vibration attenuation across a floating slab rail support system are described. Results are presented in terms of 1/2 octave band data from 25 to 1000 Hz. A particular point of interest is that this construction lies directly over a shopping center complex.

A-036 Paolillo, A.W.
Control of noise and vibration in buildings adjacent to subways.
(conference paper) in: Noise-Con 73 Proceedings, pp 152-157
Institute of Noise Control Engineering, Poughkeepsie, NY (1973).

The vibration reduction achieved with the use of 1-inch thick solid Butyl Rubber rail pads and 3/8-inch thick ribbed neoprene rail pads compared to cast-in-place wood ties was measured. Reduction of subway structure vibration over the frequency range from 12.5 to 500 Hz was substantial. The ribbed neoprene pad was shown to be consistently superior to the solid 1-inch thick Butyl Rubber pad over the entire spectrum. The reduction obtained with the ribbed neoprene pad compared to the standard cast-in-place wood tie was about 10 dB between 12.5 Hz to 40 Hz and 15 to 20 dB between 50 to 400 Hz. The data are presented in terms of 1/3 octave band spectra.

A-037 Murray, R.J.
Track Fastenings.
(report) Toronto Transit Commission, Subway Construction Branch, RD-106 (1967).

A number of resilient rail fasteners are discussed, including:

- Toronto Transit Commission fasteners with the following resilient elements:
  (a) 68 Durometer Pad
  (b) 45 Durometer Pad
  (c) 45 Durometer Rail Pad and Clip Isolation
  (d) Two 45 Durometer Pads.

- Liberty Fastening

- New York Type Fastening

- Instrac Fastener (General Tire).

Measurements were performed on the Bloor-Danforth Subway. The lowest vibration levels were obtained with TTC Double 45 Durometer Pads.

Particularly good photographs of various fasteners are included. All noise and vibration data are presented in terms of sound pressure levels and vibration velocity magnitudes with 0 to 135 Hz bandwidth. Although not presented, 1/3 octave band spectra were apparently determined. Track deflection data are included. Also, some general aspects of fastener design are discussed.

A-038 Bender, E.K.; Kurze, U.J.; Ungar, E.E.
Effects of Resiliently Mounted Track Slabs on Noise and Vibration.
(final report) Bolt, Beranek & Newman, Inc., Cambridge, MA, BBN-1878. for: Washington Metropolitan Area Transit Authority, #3Z8102 (1969).

A theoretical and experimental analysis of floating slabs. Tests were performed on two types of floating slabs at the TTC system: one slab was supported on lead-asbestos pads and polyurethane foam and the other was supported on lead strips 2 feet on center with an asphalt filler placed between the strips. The measurement results indicate little or no reduction of vibration levels achieved with these configurations. The lack of vibration isolation is clearly due to the excessive stiffness of the slab supports as would be predicted by the simple single-degree-of-freedom model of floating slabs.

A-039 Wilson, G.P.
Acoustical Analysis and Recommendations for Direct Fixation Fasteners for the WMATA Metro System.
(report) Wilson, Ihrig & Associates, Oakland, CA. for:
De Leuw, Cather & Company, Washington, DC (1970).

Design considerations for resilient direct fixation fasteners are discussed. The optimum fastener stiffness is given as that which results in a rail support modulus of about 3000 lbs/in. per lineal inch of rail. The trade-off between increased noise radiation from the rail and decreased vibration force on the invert is discussed, as well as some of the chemical and environmental properties of various proposed resilient elements. Bonded pads offer no surface abrasion and do not require precompression; the result is a simpler design than for unbonded pads. Bonded pads also provide vibration isolation for all six-degrees-of-freedom, whereas unbonded designs restrain horizontal motion with the anchor bolts. Note that BART uses a bonded Landis fastener while TTC (Toronto) uses an unbonded design. The special considerations for design of special trackwork fasteners is also discussed. Generally, stiffer fasteners may be necessary at special trackwork, but the overall rail support modulus should be limited to about 6000 lbs/in. per lineal inch of rail. This minimizes the possibility of excessive rail stresses and net displacements developing in transition regions from main line track to special trackwork. Bonded fastener elements are not recommended for special trackwork due to the difficulty of manufacturing nonstandard fasteners.

A-040 Bruce, R.D.; Bender, E.K.; Ungar, E.E.
Noise and Vibration Measurements in the Toronto Transit

Commission Subway.
(draft report) Bolt, Beranek & Newman, Inc, BBN-1899. for: Toronto Transit Commission, Toronto, Ontario, Canada (1969).

This report presents the results of a comprehensive measurement program performed on the Toronto Transit Commission subway to evaluate the effects of resiliently mounted track slabs, 24-inch and 30-inch fastener spacings and track discontinuities. The subway configurations included the triple box structure and circular concrete and steel ribbed structure. Typical measurement locations were on the rail foot, grout pad, various locations on the subway wall and bench on floating slabs and on a raised center platform on the subway station. Measurement of noise and vibration in buildings adjacent to the subway are also reported. All of the data are presented in terms of 1/3 octave band spectra.

Two types of floating slabs were evaluated, the first being the slab floated on lead asbestos pads and polyurethane foam and the second supported by lead strips and asphalt joint filler. An additional measurement compares vibration levels measured for a floated slab on lead asbestos pads with those measured for an unfloated slab. Both slabs were located in adjacent track sections of the Victoria Park Station.

A-041 Heckl, M.
Theoretically Attainable Damping of Structureborne Noise for Superstructure Without Broken Rocks.
(report) (source & citation uncertain) (date uncertain) [in German].

The maximum reduction of groundborne noise and vibration attainable with vibration isolators is determined based on the assumption that the maximum attainable reduction is limited by the airborne noise at the subway walls. However, reducing subway noise levels (by use of absorption) will further lower the limit of groundborne noise and vibration levels.

A model is presented that uses an impedance approach to calculate vibration isolation effectiveness of a rail fastener. Experimental results for vibration "isolation" with resilient fasteners were found to be 30 dB at 31.5 Hz, increasing to 43 dB at 500 Hz. Note that isolation here refers to the difference between rail and invert vibration velocity. Corresponding values of force reduction range from 0 dB to approximately 18 dB. Floating cross-ties (resiliently supported ties) are discussed, including design parameters for bending resonance and mass. Caution is given concerning application of the models to aerial structures or bridges, because of a significantly different driving point impedance at the base of the trackbed.

A-042 Sakai, T.
Control of Shinkansen railway vibrations.
(journal article) Permanent Way, 18:1/2,1-10 (1977).

This article is a discussion of criteria for groundborne vibration, human response to vibration, measurement techniques, guidelines for control of groundborne vibration, and characteristics of vibration as functions of train speed and distance from the trackway, and structure type. Viaducts with "rigid structures" are found to produce the highest "corrected" acceleration level at various distances from the track center at the ground surface. The corrected acceleration level is approximately equivalent to the weighted acceleration recommended by CHABA (Reference C-1).

The following types of structures were investigated:

- Viaduct with girder structure (aerial)
- Viaduct with embankment structure (at-grade ballast and tie)
- Viaduct with excavated structure.

Train speeds were 180 km/hr or higher. Relatively low vibration levels are indicated for aerial structures with foundations on stiff soil and large structural members. Reduction of vibration was achieved by adding ballast mats or slab mats or by increasing the track mass.

No octave band or 1/3 octave band spectra are presented, and the reference levels are somewhat ambiguous. However, vibraton velocity magnitudes as high as 0.9 mm/sec were reported at 10 to 50 meters from the track centerline. These levels were estimated to impact approximately 10,000 houses between Tokyo and Hakata.

A-043 Murray, R.J.
Investigations of Noise and Vibration in Buildings Adjacent to the Bloor-Danforth Subway.
(report) Toronto Transit Commission, Subway Construction Branch, RD-105 (1967).

Measurements were performed to evaluate groundborne noise and vibration along the Bloor-Danforth Subway in Toronto. Data are presented in terms of overall vibration velocity magnitudes in three mutually perpendicular directions and (presumably A-weighted) ground pressure levels. The results are discussed with reference to G1, H1, and M1-H1 transit vehicles. The community reaction to groundborne noise and vibration is discussed.

A-044 Tokita, Y.; Oda, A.
Characteristics of ground vibration generated by traffic. (conference paper) in: Proceedings of Internoise 75, pp 511-514. Tohoku University, Sendai, Japan (1975).

This article concerns vibration propagation from a highway in Tokyo, Japan. One-third octave band acceleration spectra are presented as a function of distance from the roadside for both soft and hard soils. The vibration due to automobile traffic show broad peaks of the 1/3 octave band vibration spectra in the frequency range of 10 to 30 Hz. An additional peak in the 1/3 octave band spectra between 3 and 4 Hz was found for automobile traffic on a highway on relatively soft soil, indicating that low-frequency vibration increases when the soil is relatively soft. Although the measurements are for automobile traffic operating on highways, the measured attenuation as a function of distance should be comparable with that for train operations on at-grade ballast and tie and perhaps in subways and aerial structures as well.

A-045 Lang, J.
Structureborne Noise Levels in U-Bahn Tunnels and the Structureborne and Airborne Noise Levels in Nearby Buildings.
(report) Research Institute for Heat and Sound Technology, Vienna, Austria, #3156/WS (1974) [in German].

This is a detailed report on measurements of octave band vibration acceleration and velocity at the rail, floor, and wall of a subway; on the floor and walls of an adjacent subway; and in an apartment building at various floor levels. A detailed report on measurement data for ground vibration below the building is also included as well as data for A-weighted noise inside the apartment building. The frequency range of the presented data extends from 8 Hz to between 125

Hz and 2000 Hz. One conclusion of the report is that A-weighted sound levels are not sufficient for describing the low-frequency rumbling noise that is characteristic of groundborne noise.

A-046 Kurzweil, L.G.; Lotz, R.
Background Document for Development of an Urban Rail Noise Control Handbook.
(draft report) U.S. DOT; Transportation Systems Center, Cambridge, MA (1978).

This overview of the general nature of noise and vibration from rail rapid transit systems, includes general discussions of groundborne noise and vibration in Section 6.

A-047 Verhas, H.P.
Measurement and analysis of train induced ground vibration.
(journal article) Noise Control Eng, 13:1,28-41 (1979).

This detailed article describes measurement techniques, measurement results, and theoretical predictions for groundborne vibration from railroad tracks in England. The main discussion concerns the propagative characteristics of vibration in soil. Vibration attenuation with distance is discussed from the point of view of line and point sources, Rayleigh and body waves, and damping proportional to frequency. In Appendix B of this article, a theoretical discussion of the partition of energy between the Rayleigh waves and body waves for line and point sources is presented. Data are given for the attenuation over a 25 meter distance of groundborne vibration at two test sites, each with different train and soil conditions.

The observed vibration spectral components are related to wheel passby frequency at 12 to 18 Hz and to sleeper passby frequency at 45 to 65 Hz. Additional peaks near 32 to 34 Hz are thought to be related to a "natural frequency of the soil." At high frequencies, the damping in the soil is very high, indicating that ground vibration components at frequencies above 150 Hz are of minor importance. Note, however, that due to the method of analysis, the percentage bandwidth at 150 Hz is on the order of 1% to 2% as compared to 10% to 20% at 15 Hz. The conclusion is drawn that for an investigation of the propagation of ground vibration, an overall bandwidth of 5 to 150 Hz is adequate. Additionally, damping in the soil is frequency related and increases linearly with increasing frequency. However, from the measurements, discernment between types of waves, e.g., Rayleigh or body waves, was not possible in that a complicated combination of wave types actually existed.

The measurement system utilized a plate set in plaster of Paris within a depression and achieved a mounted resonance of approximately 400 Hz in soil. The mounted resonance was determined by impacting the transducer through a force gage and comparing the response with the input force.

The article sums up by suggesting that whenever possible, soil samples at various depths should be taken for each measurement position to correlate with material properties of the soil. Material properties likely to be of interest are the soil composition and density, Poisson's ratio, shear modulus, and water table level.

A-048 Ishii, K.; Tachibana, H.
Field measurements of structureborne sound in buildings. (conference paper) presented at Joint Meeting of Acoustical Societies of America and Japan, Honolulu, HI.

reprint no. L10. Acoustical Society of America, New York, NY (1978).

Measurement data and theoretical models are presented for groundborne noise and vibration from subways. Measurement data are presented for vibration in buildings adjacent to subway structures, including both wood frame and reinforced concrete constructions; indoor noise levels; dominant frequencies at various points in the subway; and vibration reductions achieved with various vibration control provisions including ballast, floating ties, and ballast mats. In particular, ballast mats are considered to provide exceptional reduction of groundborne vibration.

A theoretical model is given for the prediction of vibration reduction achieved by modification of subway rail and trackbed parameters. The model is a four-degree-of-freedom model and agrees reasonably well with the measurement data. Attenuation of groundborne vibration with distance from the subway structure is also described, together with a discussion of the vibration reduction achieved by the method of trenching in the soil. Curves are given for prediction of amplification of ground surface vibration above a subway structure due to decreased earth coverage. Octave band data are presented for the frequency range from 31.5 to 2 kHz.

A-049 Heckl, M.
Vibrations from Rail Vehicle Operations.
(report) Mueller - BBM GbmH, Munich, Germany, #4253 (1973) [in German].

A letter report summarizing the results of vibration measurements performed at several subway systems in Germany. The data were evaluated to determine: the effects of distance from the source; the vibration velocity levels of subway walls and ceilings relative to floors; the relative performance of various rail support systems, including ballast, hard and soft rubber mounts, and floating slabs; and the effects of train speed. Some interesting data concerning vibration velocity levels on building foundation piles at various distances from a subway and on a building basement wall are described. The data indicate relatively little attenuation with distance from the subway.

A-050 Gutowski, T.G.; Wittig, L.E.; Dym, C.L.
Some aspects of the ground vibration problem.
(journal article) Noise Control Eng, 10:3,94-101
(1978).

The article reviews the physics of groundborne vibration, applicable building damage and human response criteria, the dynamics of vibration transducer coupling with the ground surface, and results of measurements of ground vibration from a 30,400 Joule piledriver in sandy layered soil and near the support columns of an elevated highway. Three types of transducer mounts are shown together with corresponding estimates of frequency response. Also presented is a theoretical discussion of the dynamics of a transducer mounted on soil surfaces.

A-051 Gutowski, T.G.; Dym, C.L.
Traffic generated vibration from roadway facilities.
(conference paper) in: Proceedings of Internoise 75.
pp 515-518. Tohoku University, Sendai, Japan (1975).

Groundborne vibration from automobile and truck traffic, vibration propagation in soil, and a comparison of vibration levels with criteria for human perceptibility are discussed.

In particular, formulas are given for the attenuation of vibration due to effects of geometric attenuation and damping and, in the case of tunnels, tunnel wall thickness. Measurements of ground vibration due to highway traffic are presented in terms of 1/3 octave band acceleration spectra. Many of the observations and conclusions discussed here may be applicable to groundborne vibration from subways as well, specifically the comments regarding attenuation with distance and effects of tunnel wall construction.

A-052 Toronto Transit Commission.

A. Yonge Subway Northern Extension Noise and Vibration Study.Summary and Recommendations.
(report) Toronto Transit Commission. Subway Construction Branch, Toronto, Ontario, Canada, RD-115/1 (1976).

B. Yonge Subway Northern Extension Noise and Vibration Study.Technical Support Data.
(report) Toronto Transit Commission. Subway Construction Branch, Toronto, Ontario, Canada, RD-115/2 (1979).

C. Yonge Subway Northern Extension Noise and Vibration Study.Technical Reports - Consultants. Book 1 of 2.
(report) Toronto Transit Commission. Subway Construction Branch, Toronto, Ontario, Canada, RD-115/3;1 of 2 (1976).

D. Yonge Subway Northern Extension Noise and Vibration Study.Technical Reports - Consultants. Book 2 of 2.
(report) Toronto Transit Commission. Subway Construction Branch, Toronto, Ontario, Canada, RD-115/3; 2 of 2 (1976).

E. Yonge Subway Northern Extension Noise and Vibration

Study.Technical Support Data - Ivor Road Test House Studies.
(report) Toronto Transit Commission. Subway Construction Branch, Toronto, Ontario, Canada, RD-115/4 (1976).

A group of four reports in five volumes describing a broad research effort directed toward the reduction of the groundborne noise and vibration levels along the YSNE subway. The effort included field measurements of noise and vibration, geological studies, mathematical modeling of vehicle and track system dynamics, and evaluation of various control strategies. The geological conditions in the area of YSNE, and Toronto in general, are thought to be particularly efficient for transmission of vibration.

A-053 Morii, T.
Development of Shinkansen vibration isolation techniques.
(journal article) Permanent Way, 18:1/2,11-37 (1977).

This article is perhaps one of the most detailed articles available on the efforts by the Japanese to control groundborne vibration produced by the Shinkansen Railway. Little detailed spectral information is presented making interpretation of some of the measurement data difficult. However, the general trends established by the results of measured "corrected acceleration level" are noteworthy. The corrected acceleration level is approximately the same as the weighted acceleraton level that is recommended by Reference C-1.

Measurement results of groundborne vibration at various distances from the track centerline for various types of structures and soils described as "aluvian" and "diluvian" are described. Diluvian here refers to silts and clays deposited by flood water. Diluvian soil is apparently stiffer than aluvian soils. The groundborne vibration in the diluvian soils is less than in the aluvian soils. The attenuation of groundborne vibration as a function of distance is approximately 6 dB per doubling of distance in aluvian soils, and less than 6 dB per doubling of distance in diluvian soils. Groundborne vibration levels from viaducts or tunnels are indicated as higher than for embankments or excavated ways. Of the former two, groundborne vibration levels from tunnels are similar to those from viaducts. Vibration levels tend to increase with train speed in the low speed range, but above approximately 150 km/hr, the vibration level is constant and independent of train speed. Measurement results for groundborne vibration at the soil surface at various horizontal distances from a subway structure show increasing vibration levels with increasing distance from the track centerline up to a distance of about 12 meters from the track centerline. Beyond the 12 meter distance, the level decreases with increasing distance.

A number of areas are identified as requiring significant research effort. These include: analysis of vibration sources, soil structure interaction, wave propagation in soils, vibration propagation in buildings, way structure vibration control technology, vibration control technology relating to the propagation path, building vibration control technology, criteria, prediction, and measurement techniques.

Vibration control techniques used on the Shinkansen Railway include reducing unsprung bogie mass; use of resilient wheels; control of wheel flats; and use of resilient fasteners, ballast mats, slab mats, and modified fastener spacings. One-third octave band vibration velocity spectra are presented for viaduct vibration with and without ballast mats.

The construction and design of viaducts is considered. Foundation designs include ready-made and site driven piles, single, independent multi-point, and open caisson foundations. Apparently, increasing the effective mass of the supporting soil by use of foundations with large bearing surfaces, or piles on spread footings, effectively reduces groundborne vibration.

Theoretical curves are included for an isolating layer of either soft or hard material inserted in a uniform medium and experimental data for the vibration reduction achieved with rows of sheet piles or concrete piles driven in rows parallel to the track. Evidently, the isolating thickness must be 1/20 and the depth at least 1/4 to 1/2 of the wavelength of vibration and must extend at least as deep as the foundations' piles.

A detailed discussion is presented concerning the response of building structures to groundborne vibration, the attenuation of vibration within the structure, and various control measures which may be applied to and around the building.

A-054 Manning, J.E.; Kahn, R.G.; Fredberg, J.J.
Prediction and Control of Rail Transit Noise and Vibration - A State-of-the-Art Assessment.
(interim report) Cambridge Collaborative, Inc., Cambridge, MA. for: U.S. DOT; Transportation Systems Center, Cambridge, MA, UMTA-MA-06-0025-74-5 (1974).

This report is a "critical review" of the technology for the prediction and control of urban rail transit noise and vibration with primary emphasis on parameters affecting propagation paths. Specifically included are methods for the prediction of groundborne noise and vibration from transit operation on at-grade, elevated, and subway track. Vibration controls discussed include resilient rail fasteners, floating slabs, and trenching. Appendix D discusses the propagation of noise and vibration through soil and includes a discussion of the use of circular discs for mounting accelerometers on the ground surface.

A-055 Murray, R.J.
Noise and Vibration Control of Rapid Transit Systems.
(report) Toronto Transit Commission. Subway Construction Branch, RD-108 (1967).

Various rapid transit systems throughout the world are summarized and compared. The information is useful as background material. No detailed data regarding groundborne noise and vibration are presented. A detailed discussion of soils about the Toronto Transit System is included.

A-056 Murray, R.J.
Noise and Vibration Control; Structures, Trackwork and Rolling Stock.
(report) Toronto Transit Commission. Subway Construction Branch, RD-109 (1967).

Airborne noise and structure vibration are discussed with regard to transit component design. Very little, if any, information directly concerns groundborne noise and vibration.

A-057 Nelson, J.T.
Groundborne vibration from rapid transit operations.
(conference paper) presented at Joint Meeting of Acoustical Societies of America and Japan, Honolulu, HI, (1978).

A discussion is presented regarding measured groundborne vibration at the WMATA Metro and CTA rapid transit systems. Additional data from TTC (Toronto) and MURLA (Melbourne) are also included. Ground surface vibration acceleration levels above earth-based, mixed-face, and rock subways are discussed. Vibration reductions are compared for continuous floating slabs, discontinuous "double-tie" floating slabs, and resiliently supported cross-ties. Of the floating slabs considered, the TTC discontinuous "double-tie" system gives the superior vibration reduction. Included is a discussion of the possibility in lightweight circular tunnels of dynamic interaction of the WMATA Metro type continuous floating slab in lightweight circular tunnels with the vehicle truck. One-third octave band spectra are presented of the ground surface vibration for various types of subways and founding conditions. Also presented are the measured insertion losses with several floating installations.

A-058 Rucker, W.
Measurement and evaluation of random vibrations.
(paper in monograph) in: Dynamic Response and Wave Propagation in Soils. Prange, B. (ed), pp 407-422. A.A. Balkema, Rotterdam, The Netherlands (1978).

This paper is one of a number of papers describing the theoretical and practical aspects of soil-structure interaction. Rucker describes the use of finite element analysis to investigate random groundborne vibration produced by trains operating in a double-box subway. The frequency response of the structure was analyzed with a finite element model employing 290 elements with 355 nodal points, the greatest element size being one-fifth of the shortest wavelength of the shear wave in soil. The model was applied to an existing structure at which measurements of, vibration power-spectral density were performed. The soil's shear modulus of elasticity and Poisson's ratio were determined by cross-correlation of the signals from two measurement points at different locations, using groundborne vibration from the trains. The measured vibration power-spectral densities at and within the surrounding soil, on the tunnel wall, ceiling, and on the rail were combined with the frequency response of the structure determined by the finite element model to determine the input power spectrum of the "excitation process." All measurement data are presented in terms of constant bandwidth frequency analysis over the range of 0 to 100 Hz. The data are sufficiently detailed to estimate the reduction with distance of vibration within and at the surface of the soil. Significant spectral components were observed for soil vibration in the ranges of 15 to 30 Hz and 48 to 75 Hz. Also, subway wall and ceiling measurements indicate the presence of low-frequency vibration between 10 and 15 Hz. The vertical invert vibration spectra data are very different from the wall and ceiling vibration spectra. Finally, a theoretical discussion of the various transfer functions and representations is presented, together with a description of the measurement and data analysis systems.

A-059 Gutowski, T.G.; Dym, C.L.
Propagation of ground vibration.
(journal article) J Sound Vibr, 49:2,179-193 (1976).

A review of the 1976 state-of-the-art for prediction and measurement of ground vibration is presented, including review of theoretical models of vibration attenuation. Measurement data and theory are compared and combined into a predictive model. The theoretical discussion of vibration propagation includes the various types of waves, e.g., shear, compression, and Rayleigh, which may be produced by elevated, at-grade, or sub-grade structures. Attenuation of each of these wave types is discussed with regard to geometric and dissipative effects. The discussion of dissipation is a major part of this paper. In particular, dissipative attenuation in dB was found experimentally to be proportional to the logarithm of the number of wavelengths between the two points in question. This logarithmic relation is in contradiction with the usual theoretical models of damping proposed by Barkan and others, namely that the amplitude attenuation in dB be of the form:

$$-8.7ax \qquad \text{(frequency independent)}$$

or

$$-8.7 \frac{nx}{\lambda} \pi \qquad \text{(proportional to the number of wavelengths)}$$

where "x" is the distance parameter, "a" is some damping coefficient, "n" is a dimensionless loss factor, and λ is the wavelength. Data are also presented which conform with the second equation. Representative soil absorption coefficients for the first equation are:

	a (1/ft)	a (1/m)
Water saturated clay	0.012-0.037	0.040-0.120
Loess and loessial soil	0.030	0.100
Sand and silt	0.012	0.040

For the second equation, typical values are:

	n (per wavelength)
Clay	0.50
Loess	0.30
Sand	0.10

Measurement techniques are described in terms of frequency response, including the effects of transducer-soil coupling.

A-060 Prause, R.H.; Arnlund, R.C.; Harrison, H.D.
Measurement Plan for the Characterization of the Load Environment for Cross-Ties and Fasteners.
(interim report) Battelle-Columbus Laboratories, Columbus, OH & Bechtel, Inc. for: U.S. FRA; Office of Research and Development, FRA/ORD-77/03 (1977).

This report was prepared as part of the Improved Track Structures Research Program sponsored by the Office of Rail Safety Research of the Federal Railroad Administration. The report is a planning document for a track measurement program to obtain data on the service loads and reactions of cross-ties and rail fasteners. These data will be used to validate analytical models for predicting track response and to provide a statistical description of track loading for design and testing improved cross-ties and fastener assemblies. The report includes criteria for site selection, an evaluation of measurement parameters, instrumentation and data analysis techniques, and the development of statistical criteria for planning the measurement program.

Of particular interest is the recommended transduction system for measuring rail fastener forces. The system includes the use of a specially designed tie plate with piezoelectric load cells to measure the force between the fastener and rail foot. Additional "load washers" are recommended to monitor the variation of bolt tension, which is assumed to be about 1/10 to 1/20 of the variation of dynamic forces transmitted through the rail seat, for the type of rail fastening considered. A specially designed load cell tie developed by the Federal Railroad Administration/Portland Cement Association is also discussed, which in addition to providing data on rail fastener forces, also allows the measurement of tie bending stresses.

This report is primarily concerned with problems of dynamic and static loads and not specifically groundborne vibration. However, these force measurement methods are applicable to studying vibration energy transmission through the fastener.

A-061 Ahlbeck, D.R.; Harrison, H.D.
Techniques for measuring wheel-rail forces with trackside instrumentation.
(conference paper) presented at Winter Annual Meeting of ASME, Atlanta, GA, reprint #77-WA/RT-9 (1977).

This paper is a discussion of the measurement and analysis of vertical and horizontal wheel/rail forces with the use of welded strain gauges. The measurement of fastener forces is not discussed.

A-062 Saurenman, H.J.
Criteria for acceptable levels of building vibration caused by rapid transit operations.
(conference paper) presented at 99th Meeting of the Acoustical Society of America, San Francisco, CA, paper #Z8 (1980).

This paper presents the results of an evaluation of 15 cases in which structural vibration from transit trains was measured. The acceptability of the vibration environment was divided into four categories (imperceptible, barely perceptible, definitely perceptible, and disagreeable) based on the subjective assessment of the building occupants and of the person who took the measurements. The results of the analysis indicate that the limits previously applied to residential vibration were not sufficiently restrictive in many cases; they also imply possible appropriate limits.

The vibration was evaluated using the weighting curves proposed by CHABA Working Group 69 (Ref. C-1) and the weighted vibration level was found to correlate the wall with the subjective human response to building vibration.

A-063 Dawn, T.M.; Stanworth, C.G.
Ground vibrations from passing trains.
(journal article) J Sound Vibr, 66:3,355-362 (1979).

This paper presents a general discussion of groundborne vibration from passing railroad trains. The topics considered include:

- Generation
- Vibration propagation
- Building response
- Experimental observations.

The theoretical discussion includes the characterization of vibration propagation in soils in terms of compression, shear, and Rayleigh waves. The experimental data presented include 1/3 octave band spectra for building foundation, ground floor, and first floor vibration relative to the adjacent ground, over a frequency range of 2 Hz to about 80 Hz. Data for both vertical and transverse wall vibration is presented. Evidently, very little coupling loss exists between the foundation and adjacent soil up to 20 to 31.5 Hz. At higher frequencies, the loss increases rapidly. However, an amplification of about 20 dB was observed for ground floor and first floor vibration relative to the adjacent ground vibration. Attenuation is called to the possibility of train speeds exceeding the shear wave or Rayleigh wave propagation velocity in some soils, thereby producing a kind of "shock wave." For shear wave velocity of 150 m/sec, such a train speed would be about 500 km/hr, significantly higher than present day train speeds.

A Campbell diagram is presented which indicates that the frequencies of the spectral peaks in the building wall vibration spectra increase with increasing train speed. These peaks are therefore attributed to roadbed perturbations with specific wavelengths characteristic of the roadbed. These perturbations include:

- Cross-ties
- Long wavelength corrugations due to rail straightening machine
- Rail welds
- Car length.

The unsprung mass of the vehicle is believed to be of less importance than the gross weight of the vehicle. However, high stiffness of the bogie shock absorbers is believed to have increased the effective mass of the vehicle bogie on one of the train types considered. Tests are being planned to investigate this. The measurement data were collected by the Research and Development Division of British Railways.

A-064 Ahlbeck, D.R.; Harrison, H.D.; Tuten, J.M.

Measurement of Wheel/Rail Forces at the Washington Metropolitan Area Transit Authority. Vol II: Test Report. (interim report) Battelle-Columbus Laboratories, Columbus, OH, DOT-TSC-UMTA-80-25,II. for: U.S. DOT; Urban Mass Transportation Administration, UMTA-MA-06-0025-80-7. avail: U.S. National Technical Information Service, PB81-103327 (1980).

A-065 Koch, H.W.
Comparative values of structureborne sound levels in track tunnels.
(journal article) J Sound Vibr, 66:3,377-380 (1979).

A summary of the effects of tunnel wall thickness and trackbed configuration on groundborne vibration from subways and railroad tunnels is presented. A chart is provided giving the subway wall vibration velocity level in dB as a function of tunnel wall thickness. Measurement data plotted against an empirically determined formula fall within 2.5 dB of the formula value. The line is given as:

L(dB re 5 micro-cm/sec)= (69 to 56) * log(v/40)

for subway train speeds of about 60 km/hr. German main line trains (100,000 to 120,000 N axle load) produce about 10 to 11 dB higher levels than subway trains (50,000 N axle load). Vibration levels were found to decrease by about 4 to 7 dB over a running period of about 4 years. "Settling" of the tunnel over this time is conjectured as responsible for the reduction. Insertion of an intermediate layer of sand beneath the ballast produced an increase of vibration levels by about 3 to 8 dB while reducing the peak frequency from 63 to 50 Hz. Increasing the ballast thickness from 30 to 40 cm to 70 cm produced a 5 dB reduction of vibration. Quantitative 1/3 octave band data are presented for the rail, invert, tunnel wall, and an adjacent cellar ceiling. Additional 1/3 octave band data are presented for trains with higher axle loads than subway trains. The frequency range is limited to 25 to about 200 Hz.

A-066 Koch, H.W.
Propagation of vibrations and structureborne sound caused by trains running at maximum speed of 250 km/hr.
(journal article) J Sound Vibr, 51:3,441-442 (1977).

Results of measurements of groundborne vibration at distances of 7.5, 15, 30, 50, and 100 m from the tracks of the Deutsche Bundesbahn test track for high-speed trains near Rheda-Oelde, Westphalia are presented. The transducers consisted of moving-coil instruments (velocity transducers) with a resonance frequency of 4.5 Hz. An additional velocity transducer with a resonance frequency of 14 Hz was placed on the rail. The maximum amplitudes of vibration velocity in the frequency range of 15 to 30 Hz generally decreased approximately as the reciprocal of the distance from the track. Amplitudes of vibration for trains traveling at speeds of 230 to 240 km/hr exceeded by 30% to 40% those produced by trains traveling at about 200 km/hr. At 100 m from the track, the maximum amplitude of vibration was about .08 to .12 mm/sec. Figures are presented illustrating the variation of vibration velocity and structureborne sound (dBA) as a function of distance from the track. No spectral data are presented.

A-067 Johnston, G.W.
Assessment of groundborne vibration to the ground from subway trains; ground load modeling.
(paper in report) in: Yonge Subway Northern Extension

Noise and Vibration Study; Vol IV, RD-115/3. Toronto Transit Commission, Subway Construction Branch (1976).

This report is part of a large report published by the Toronto Transit Commission (see reference A-052) concerning groundborne noise and vibration from the YSNE subways. The approach in this section uses the concept of mechanical impedance to characterize the dynamics of wheel/rail interaction, vibration isolation, and vehicle truck effects. The modelling encompasses the frequency range of 20 to 200 Hz and included an eight-degree-of-freedom model of the vehicle. The subtopics covered in the report include:

- Rail force transfer function
- Rail and wheel random input data
- Wheel impedance including connected vehicle components
- Rail impedance, including isolation system
- Ground plane forces
- Applications of models to :
  - Wheel Alone-single degree rail isolation
  - Two degree rail isolation [Lawrence, STEDEF]
  - Resilient wheels [Penn]
  - Flat wheel sources
  - Flexible axle gear box.

One conclusion is that the truck can be effectively modeled with a lumped mass system consisting of:

- Mass of a single wheel
- Axle mass [rigid body and first bending mode]
- Gear box mass [attached to axle].

Impedance formulas are presented for rigid and resilient wheels. The first axle bending mode frequency was found experimentally to be 119 Hz. Higher bending mode frequencies were above 450 Hz, allowing the higher axle modes to be neglected. The primary suspension resonance was estimated to be 5 to 10 Hz. For stiffer suspension, additional masses representing the truck frame may have to be included. Impedance formulas are presented for rails with both single-degree-of-freedom systems such as the "Lawrence" system. Finally, formulas for calculation of "ground plane" forces are given. The discussion of the results of the modelling effort is very detailed. Quantitative estimates of vibration reduction relative to the Standard TTC track configuration are given for various combinations of vibration control concepts, including: reduction of unsprung truck mass, use of heavier gauge track, addition of mass to existing rails, reduction of isolator stiffness, and use of a vibration absorber on track axles. Increasing the rail mass gave, at most, a 2 dB theoretical decrease in ground force, as the mass of the wheel is the controlling factor. Vibration absorbers on the axles may provide about 10 dB reduction of vibration at peak response frequencies. The two-degree-of-freedom track support system gives 5 to 10 dB theoretical reduction, depending on design. Resilient Penn wheels as proposed for the TTC system would provide no reduction of vibration at about 40 to 50 Hz and would add a second resonance at about 80 Hz, leading to unpredictable usefulness for vibration control.

A-068 Hunt, A.D.
Manufacture and Installation of the Track Vibration Isolation Systems on the Spadina Subway.
(technical report) Toronto Transit Commission, Toronto, Ontario, Canada (1976).

This report is a continuation of the 1975 Technical Report on the same subject and photographically covers the manufacture and installation of the discontinuous floating, double-tie, and crossover track vibration isolation systems for the Spadina Subway.

The precast discontinuous double ties are shipped to the subway construction site, where they are placed in their final locations in the subway with forklifts. The slabs are then positioned with clamps and hydraulic jacks on the rubber support, side, and spacer pads. The crossover slabs are poured in place, using sheet-metal forms and conventional techniques. Type A3 double ties are included for use at transition sections between rigid invert and floated trackbeds. The type A3 double tie is similar to the standard type A double tie, except that recesses are included for up to nine support pads rather than four. The double tie nearest the rigid invert is supported by nine pads, the rest by eight pads, and so forth, providing a transition to the standard double tie supported by four pads.

A-069 Kazamaki, T.
Subway Vibration Control.
(journal article) Permanent Way, 18:1/2(issue 66-67) 38-53 (1977)

This article is a comprehensive article on groundborne noise and vibration control at a number of Japanese railway lines. Measurement data are presented which illustrate the difference in vibration level between the subway inverts, walls, and ceilings of adjacent tunnels or double box sections with trains running at 40 to 60 km/hr. Vibration levels are given for the following noise control provisions relative to concrete invert, ballasted track, vibration damping sleeper type PL4, vibration damping sleeper type PV3, and ballast mat.

Of these four control measures, the ballast mat gave the greatest vibration reduction. However, the tunnel in which the ballast was tested was evidently three times heavier than the standard tunnel, making comparison difficult. A four-degree-of-freedom model of the vehicle, rail, fastener, trackbed, and tunnel structure is presented for prediction of the effects of the above noise control provisions, with moderate agreement with experimental data.

Vibration control applicable to the tunnel includes increasing the tunnel mass and wall thickness and use of a resilient lining about the tunnel exterior. Some experimental data are presented concerning the attenuation of vibration as a function of distance from the tunnel. The use of renching is considered, including the use of closed-cell urethane foam as an isolation medium.

The 63 and 125 Hz octave bands are the most significant. Indications are that the axle shaft and gear box resonate in the neighborhood of 60 Hz, indicating that the unsprung portion of the vehicle is the most important with respect to tunnel vibration. Wheel flats and rough rail evidently amplify rail vibration in the neighborhood of 100 to 300 Hz by a factor of 6 to 12 dB. Even minor rail irregularities are indicated as being very important in terms of vibration generation. Satisfactory maintenance of rails and wheels is indicated to be very important, including accurate maintenance of track gauge and elevation.

Numerous examples of measurement data are presented, including octave band spectra as well as a weighted acceleration abbreviated as "gal." The octave band spectra include data for subway structure vibration, building vibration and noise, and vibration reduction effectiveness of various noise control techniques. The frequency range of the spectral data extends from 31.5 Hz to 1000 Hz. No data are presented for frequencies below 31.5 Hz. Tables are included for presentation of frequencies at which significant maxima were observed.

A-070 Paterson, W.H.; Wilson, G.P.
Melbourne Underground Rail Loop - Track Support, Noise and Vibration.
(report) W.H. Paterson, Toronto, Canada and Wilson, Ihrig & Assoc., Oakland, CA. for: John Connell-Mott, Hay & Anderson, Hatch, Jacobs, Melbourne, Austrailia (1974).

The rail support configurations considered for use on the MURLA subway system were ballast and tie, resilient direct fixation, resiliently supported ties, continuous floating slab, and the discontinuous floating slab. The descriptions of these systems are very clear and well presented , but no performance data are included. The conclusions of the report are:

1. Ballast and tie track are not recommended for the MURLA tunnel.

2. Direct fixation resilient fasteners such as the TTC, Pandrol, or Landis fastener would give reasonably satisfactory results, but additional isolation at low frequencies may be desirable.

3. Continuous floating slabs are desirable with respect to vibration isolation, but are not recommended due to cost, problems with installation, and noise in tunnels.

4. The discontinuous floating slab is recommended.

5. The RS-STEDEF system best fulfills the design criteria.

6. 60 kg/m (121 lbs/yd) rail with 30-inch fastener spacing is recommended to optimize noise and vibration performance and provide some economy in the total number of fasteners required.

Design considerations are discussed for each of the recommended track support configurations. The methods of installation and track alignment are also discussed.

A-071 Copley, L.G.
Design Analysis Report for Groundborne Noise Control - MBTA Red Line Extension N.W. (Harvard -- Davis).
(report) L.G. Copley Associates, Newton, MA. for: Bechtel, Inc. (1979).

Groundborne noise and vibration levels along the MBTA Red Line Extension N.W. are predicted. The prediction procedure is based on the methods of Ungar and Bender (Ref. A-81) and the parametric approach proposed by Kurzweil and Lotz (Ref. A-1). The analysis includes the effects of:

- Geometric spreading
- Dissipation loss
- Geological layering, including bedrock
- Train speed
- Track structure, including resilient fasteners, floating slabs, and an insulated slab
- Tunnel liner structure effect, including soil or rock founding conditions.

The coupling of the tunnel with the surrounding soil is discussed in terms of the specific impedance of the soil, the mass per unit area of the tunnel wall, and an assumed driving force per unit area, which is unknown but assumed to be independent of tunnel structure parameters. Note is made in the report that this model ignores the bending stiffness of the tunnel wall, so that the model may underpredict the additional attenuation obtained by thickening the wall. That is, the wall bending stiffness is probably more significant than the wall mass per unit area, as evidenced in data presented by Kurzweil and Lotz. The effect of soil layering is considered by computing the transmission coefficient at each interface under free-field conditions and multiplying all of the coefficients together to obtain the effective transmission coefficient for the entire geological structure. Because the specific impedance of soils is generally less for layers closer to the surface than for deeper layers, the overall effect is an amplification of vibration amplitude at each layer. The analysis does not include the effect of resonance within the soil layers. The model uses as a starting point a reference A-weighted sound level that was determined by measurements along the existing Red Line with corrections for local soil conditions and distances from the tunnel. The reference distance is simply that of the tunnel wall. Geometrical spreading loss is computed in terms of distance from the center of the structure. Contained within the report are a number of soil survey maps containing bore hole data for the Red Line Extension. The final product of the analysis is a graph of the A-weighted noise level in the cellar as a function of location along the alignment.

A-072 Nolle, H.
Double Sleeper Track and RF-Stedef Track Vibration Survey at Jolimont, November 1977.
(preliminary report) Melbourne Underground Rail Loop Authority, Melbourne, Australia (1978).

Vibration levels were measured at various locations at surface installations of RS-STEDEF resiliently supported ties and discontinuous double tie floating slabs such as used on the TTC (Toronto) system. Measurement locations were at various distances from an open cut section of track. The STEDEF and double tie systems were installed at adjacent sections of track, thus removing variation in ground characteristics from the comparison. Transducers were mounted horizontally and vertically on mudstone bedrock at about 3 to 6 m below the soil surface at various distances from the track, between the tracks, on the centerline of the double tie centerline, and on the edge of the concrete invert of the double tie track. These tests were subsequent to tests reported earlier for ballast and tie and STEDEF track sections. The ballast and tie track was removed and replaced by the double tie floating slab system. Both track installations were founded on mudstone bedrock.

Narrowband and 1/3 octave band vibration levels are presented. The 1/3 octave band data are for vibration recorded between the two track installations. Substantial reduction of vertical vibration was achieved with the double tie system relative to the STEDEF system at all frequencies between 20 and 500 Hz, reaching about 20 dB at 100 to 300 Hz, with 1 to 2 dB amplifications at the design resonance frequency of 16 Hz. Below 16 Hz, vibration reduction of several dB is evident. Reduction of horizontal vibration by the floating double tie system is significant over the entire frequency range of 10 to 500 Hz.

The vibration data as a function of distance are fitted with an attenuation model described in a previous report (A-78). The least attenuation with distance was found at 16 to 20 Hz. Part B of this report consists of tabulating results of the curve fitting analysis.

A-073 Wilson, G.P.
Groundborne Vibration and Noise Measurements and Analysis - 61 Rockmart Drive.
(letter report) Wilson, Ihrig & Associates, Oakland, CA.
for: Metropolitan Atlanta Rapid Transit Authority (1980) [proprietary information].

This letter report concerns measurements of groundborne noise and vibration at a residential structure located approximately 100 ft from an at-grade ballast and tie section of the West Line track on the MARTA system. One-third octave band data are presented for eastbound and westbound trains at approximately 55 to 65 mph. The measurements include vibration and noise in the at-grade living room and bedroom and in the basement living room and bedroom. Vertical vibration was measured on the floors of these rooms. The basement room floors are essentially concrete slabs poured directly on the ground. The vibration data span the frequency range of 3.15 to 1250 Hz, while the acoustic data span the frequency range of 12.5 to 5000 Hz.

The data indicate very similar vibration spectra for both eastbound and westbound transit trains, and almost similar spectra measured during passage of a freight train, neglecting the engine, at a distance of about 420 ft. The vibration data include spectral peaks in the range of 16 to 25 Hz, the frequency peaks being higher on the first floor than in the basement. Evidently, structural resonances of the floor have frequencies in the neighborhood of 16 Hz.

The transit vehicle truck is considered as possibly responsible for the vibration levels measured here. The measurement data reported by Wolfe of WIA regarding the effects of truck design are cited as an example. Also, the measurement data obtained by NYCTA regarding the Rockwell trucks are cited. (Rockwell trucks are used on the MARTA system.) Additional rail grinding and wheel truing did not substantially reduce vibration at this location, as evidenced by tests conducted after finishing of a rough weld and resurfacing at other locations.

A-074 Fox, G.D.
Design of Light Rail Track in Pavement.
(report) De Leuw, Cather & Company, San Francisco, CA.
(citation uncertain) (date uncertain).

This paper describes various light rail vehicle track designs for use in at-grade pavement. Several of the designs discussed include both conventional and resiliently supported track. The resiliently supported tracks discussed are:

- Full depth ballast
- Ballast base, block pavement
- Ballast base, precast slab pavement
- Slab base, block pavement
- Slab base, precast slab pavement
- Slab base, concrete pavement.

Descriptive diagrams are included for each of these concepts. The paper presents method for constructing the basic resilient configurations of ballast base and slab base tracks and compares European resilient track design with U.S. designs for cost, noise, maintenance, and urban design. Fox provides data from various track designs which indicate that noise from resiliently supported track can be as much as 5 to 10 dB less than the rigid track designs. The data include results published by Wilson, Ihrig & Associates for the San Francisco

Muni system. No data are given concerning the relative vibration of pavement surface caused by the various track designs.

A-075 Allen, P.W.; Lindley, P.B.; Payne, A.R. (eds).
Use of Rubber in Engineering.
(first edition) McLaren & Sons, Ltd., London, England (1967).

This book is a collection of papers presented by various authors at a conference on the use of rubber in engineering. The topics include the chemical, static, and dynamic properties of rubber and the manufacture or compounding of rubber, use of rubber as bridge bearings, rubber suspension systems, isolation of buildings from groundborne vibration, and other vibration control applications. The paper on building vibration isolation from groundborne vibration discusses some of the problems of isolation of buildings when the building is constructed of lightly damped beams and plates. In this case, the isolation achieved may be compromised by resonant amplification of building elements. The paper on vehicle suspension systems includes a discussion of rubber springs for railway and rapid transit vehicles, with respect to ride quality and stability.

A-076 Hunt, A.D.
Track Vibration Isolation System for the Spadina Subway.
(technical report) Toronto Transit Commission, Toronto, Ontario, Canada (1975).

The design and testing of the precast floating double ties (also referred to as the discontinuous floating slab) used on the Toronto Transit Commission system for vibration isolation are discussed. Test results are included for the rubber pads that support the floating slabs, including horizontal and vertical load deflection curves. One section describes loaded and unloaded resonance frequencies of floating slabs, within both circular tunnels and box subways. These frequencies are:

- Circular tunnels, loaded: 15 to 17 Hz
- Circular tunnels, unloaded: 21 to 23 Hz
- Box subway, loaded: 12 to 14 Hz
- Box subways, unloaded: 16 to 17 Hz

The dynamic and static stiffness for the support, side, and spacer pads are provided, which show the dynamic stiffnesses to be all slightly higher than the corresponding static stiffnesses. A continuous floating slab design is described for use at crossovers. This slab will be laden with ballast and cut longitudinally to isolate the line tracks from one another. One particularly interesting statement is that floating slab systems, such as the double tie system, are necessary for all underground structures on the Spadina Line to provide sufficient noise and vibration reduction.

A-077 Remington, P.J.; Rudd, M.J.; Ver, I.L.
Wheel/Rail Noise and Vibration; Vol 2: Applications to Control of Wheel/Rail Noise.
(final report) Bolt, Beranek & Newman, Inc., Cambridge, MA.
for: U.S. DOT; Transportation Systems Center, MTA-MA-06-0025-75-11. avail: U.S. National Technical Information Service, PB-244-515 (1975).

The focus of this report is on wheel/rail noise and vibration control in the frequency range of 200 to 1000 Hz. Of particular interest to groundborne noise and vibration is an evaluation of a rail roughness measuring device or profilometer. The radial driving point impedance of resilient wheels is considered theoretically and experimentally. The web-tire resonance frequency is evidently about 100 Hz, but additional resonances occur at 300 Hz and higher. The impedance measurements suggest that no vibration reduction will be achieved with resilient relative to standard wheels below 300 Hz. However, measurement errors are mentioned with respect to these data.

A-078 Nolle, H.
Ballasted and RF-Stedef Track Vibration Survey at Jolimont, November 1976.
(report) Melbourne Underground Rail Loop Authority, Melbourne, Australia (1977).

The vibration isolation performance of the R.S. STEDEF resiliently supported tie track relative to an adjacent ballast and tie track was evaluated at an open cut section at the Jolimont test track, Melbourne. Measurement data including spectra are presented for a variety of measurement locations. The concrete slab for the R.S. STEDEF system and the ballast were placed directly on bedrock. Measurement were taken on the slope of an open cut and at various distances up to 58 m from the track with transducers mounted directly on mudstone bedrock 3 to 6 m below the soil surface. Thus, the vibration levels obtained are representative of those for vibration propagation in rock. Both horizontal as well as vertical measurements are reported. A model for the amplitude of vibration as a function of distance is described as:

$$a(x) = \frac{A}{(1+kx^n)}$$

where "A" is the amplitude at the source, "a(x)" is the amplitude at a distance "x" from the source, and "k" and "n" are empirically determined constants. This formula was numerically fitted to the experimental 1/3 octave band data measured at various distances from the source, an iterative least-square technique. The results for A, K, and n are found to vary with frequency. The total error associated with the curves is on the order of 1 to 2 dB over the frequency range of 12.5 to 400 Hz. Errors on the order of 0.1 dB to 0.5 dB are common. Typical values of k and n are 0.2 to 2 dB for k and 1 to 2 dB for n. The results indicate low attenuation at 16 Hz and maximum attenuation at 400 Hz.

Three different train types were used for testing. Although Nolle indicates that little difference exists between train types, the 1/3 octave spectra show significant differences. The data indicate a rise of level with increasing train speed. No general relation is given. The relative performance of the R. S. STEDEF ballastless and ballast and tie track are as follows:

- Between 8 to 40 Hz, the STEDEF system produced 5 dB lower vibration levels at 40 to 60 km/hr.

- Between 40 and 200 Hz, no significant differences were observed.

- Between 200 and 800 Hz, the STEDEF system produced 5 dB lower levels at 40 and 60 km/hr and 3 dB lower levels at 20 km/hr.

A-079 Powell, J.K.
MURLA Project - Comments on Dr. Nolle's Letter to Mr A.D. Hunt - October 6, 1977.
(research memo) Toronto Transit Commission. Engineering

Department, #494 (1977).

The subjects included in this discussion are:

- Specification of ballast
- Mounting of transducers on soil surfaces
- Frequency response of the measurement system
- Relation between ground vibration from an open cut and from a subway structure.

Octave band data are presented for vibration at the ground surface for subway and surface trains and for subway structure vibration and embankment vibration. Comparisons are given between wood tie and ballast, concrete ties and ballast, and subway structure vibration. The data are taken from the YSNE Noise and Vibration Study, Toronto Transit Commission Report No. RD 115/2 and RD 115/3.

A-080 Waller, R.A.
Building on Springs.
(first edition), Pergammon Press, Oxford, England (1969).

The author discusses in this short test the fundamental of designing buildings with vibration isolation to reduce levels of groundborne vibration from such sources as railroads and rapid transit systems. The contents include:

- Vibration sources
- Acceptable levels of vibration
- Vibration design
- Effects of wind
- Specification and choice of springs
- Detailed design of springs
- Local resonance
- Effect of building on springs on constructions and architectural details

- Costs and benefits.

The book is not mathematically oriented, but rather presents a general discussion with the aid of tables and design charts.

A-081 Bender, E.K.
Rail Fastener Design for Noise and Vibration Control. (report) Bolt, Beranek & Newman, Inc., Cambridge, MA, BBN-2485. for: New York City Transit Authority (1974).

The effects of fastener design on airborne noise and structureborne noise and vibration are analyzed. The basic conclusions are:

1. Noise and vibration in rail cars will be influenced only slightly by fastener parameters.

2. The groundborne noise level in buildings near subways will be proportional to 20 log(K), where "K" is the fastener stiffness.

3. Resiliently mounted ties are expected to reduce noise in neighboring buildings only above 250 Hz.

Formulas are presented for calculation of wheel and rail impedances.

The rail and wheel impedances are compared and found to be similar at about 40 to 90 Hz. Above 100 Hz, the rail motion becomes large in comparison with the wheel motion. Below 100 Hz, the wheel impedance may be underestimated because the truck mass and primary stiffness are excluded. The effect of fastener stiffness on noise transmitted to buildings is summarized as:

Frequency Range	Effect
10 to 30 Hz	~ 5 log(K)
>100 Hz	~ 20 log(K)
30 to 100 Hz	(not given)

One-third octave band data measured on the NYCTA system are presented which indicate the difference in subway structure vibration between fasteners with stiffnesses of 500,000 lbs/in. and 120,000 lbs/in. The differences are consistent with projections above 250 Hz, but become less at lower frequencies; between 50 and 125 Hz, the reduction is approximately 3 dB, while between 31.5 and 40 Hz, some amplificaton is evident.

No data are presented below 31.5 Hz.

Resiliently mounted ties are discussed with the conclusion that at low frequencies, the tie is not expected to offer any improvements in vibration isolation. At higher frequencies, e.g., above the resonance frequency of the tie and rail on the elastic support, the two-stage isolator performance of the resilient tie system gave 9 dB lower vibration than the ballast and tie track.

A-082 Dupin, G.; Levy, T.
Attenuation du son dans un milieu poreux elastique. (Sound attenuation in an elastic medium).
(journal article) Acustica, 44:1,10-13 (1980) [in French].

A theory is developed for the propagation of waves in a porous elastic solid containing a compressible viscous fluid using a homogenization process. Boundary conditions are given, for macroscopic variables, for the interface between such a porous medium and the adjacent free flow. The theory is applied to an incident plane acoustic wave entering into such a medium. This paper may have some limited relevance to propagation of groundborne vibration in soil.

A-083 Remington, PJ; Rudd, MJ; Ver, IL.
Wheel/Rail Noise and Vibration; Vol 1: Mechanics of Wheel/Rail Noise Generation.
(final report) Bolt, Beranek & Newman, Inc., Cambridge, MA.
for: U.S. DOT; Transportation Systems Center, UMTA-MA-06-0025-75-10. avail: U.S. National Technical Information Service, PB-244-514 (1975).

The final results of a project reported here are under the UMTA Urban Rail Supporting Technology Program to develop a basic understanding of urban transit wheel/rail noise control measures. Analytical models of impedance, resonance, radiation efficiency, and directivity of wheels and rails are presented and compared with field and laboratory measurements. Analytical formulas for the prediction of noise in the three general categories of wheel/rail noise -- squeal, impact, and roar -- are presented and verified by comparison with laboratory measurements as well as field measurements using a small steel-wheeled personal rapid transit vehicle on a test track. In general, the agreement between the predictions and the measurements is adequate to verify the formulas, although uncertainties in the wheel/rail stick-slip curve and significant variations in roughness across the faces of wheels and rails (measured by a device developed during the program) lead to some uncertainties in the squeal and roar predictions. Formulas and measurement data for vertical and lateral rail driving point impedance and wheel tire driving point impedance are presented. The rail support resonance is identified between 90 and 140 Hz, and fastener spacing effects are observed at a bending wavelength equal to twice the fastener spacing, about 800 Hz. The frequency range is restricted to 200 Hz to about 1000 Hz. In this frequency range, the rail is modeled as a free infinite beam, and the wheel radial driving point is modeled as that of the sum of the wheel mass and 1/3 of the axle mass. Very significant resonances are noted in the axial driving point impedance of the wheel over this frequency range. No discussion is presented concerning groundborne vibration.

A-084 Anonymous
On the right track.
(journal editorial) Rubber Dev, 32:3,68-70 (1979).

This short article notes the use and design of ribbed rubber sleeper shoes to reduce the structural vibration of the Vienna Floridsdorfer Bridge. Sleepers were manufactured of polyurethane. No measurement data are presented.

A-085 Steffens, R.J.
Structural Vibration and Damage. Some Notes on Aspects of the Problem and a Review of Available Information.
(report) Great Britain, Dept of the Environment, Building Research Establishment. Her Majesty's Stationary Office (1974).

This report is a review of literature and theoretical methods for evaluation of structural vibration and damage of buildings. Among the topics covered are:

- Factors involved in structural response
- Natural frequencies of buildings and other structures

- Natural frequencies of building elements
- Damage criteria.

Of these, the discussion of natural frequencies, human sensitivity, and criteria for damage are most important. Calculation methods for building elements are presented, e.g., for beam windows and floors. The natural frequencies of building elements can be arranged as follows:

Element	Frequency
Floors	
Floors and slabs	10 to 30 Hz
Steel joist and concrete slabs	6 to 20 Hz
Suspended concrete floors	20 to 45 Hz
Window panes	10 to 100 Hz
Plaster Ceilings	10 to 20 Hz
Beams	5 to 50 Hz

The discussion of human sensitivity includes:

- Diekmann K-values
- Standard DIN 4025 (1958)
- Standard DIN 4150
- Standard DVI 2057 (1963)
- Other methods.

Charts and formulae are presented for evaluation of human sensitivity. A discussion of groundborne vibration from rail traffic is included which is concerned primarily with overall displacement or acceleration data as reported in the literature. No spectra are presented.

A-086 Sato, Y.
High-frequency vibration of track.
(journal article) Permanent Way, 5:3,1-15 (1962).

This entire article is concerned with high-frequency track vibration from about 100 Hz to as high as about 3 kHz. Simple multi-degree-of-freedom models of the rail, fastener, ballast, and associated stiffness are described. The first resonance frequency of this system is about 43 Hz looking into the rail.

A-087 Sweezie, H.M.
Installation of the double tie, concrete slab, isolated trackbed.
(conference paper) presented at APTA Rapid Transit Conference, Toronto, Ontario, Canada (1976).

This short paper considers the construction and installation of the discontinuous double tie floating slabs in the Toronto subways.

A-088 Anonymous
Advanced Transport Technology - Track.
(report) British Railways Research Department, (citation uncertain) (date uncertain).

Part 300/301 of this report is concerned with track dynamics. The use of computer programs for determining wheel/rail forces and responses are discussed with respect to a variety of rail or wheel discontinuities. Typical track/vehicle system response curves are given which indicate a very strong resonance in the neighborhood of 30 Hz. The presence of discrete rail supports is indicated as producing a cyclicly varying apparent stiffness at the top of rail as seen by the vehicle. Under certain conditions, self-excited instabilities may occur.

A-089 Sato, Y.; Umekubo, S.; Hirata, G.; Arai, M.; Chino, T. et al.
Resilient rail.

(journal article) Quarterly Reports, 13:2 (1972).
[Japanese source, in English]

This report concerns a unique type of continuous resilient rail support designed to reduce noise and vibration on elevated track. The resilient rail is an assembly of continuous rubber strips fastened to both sides of the rail web with clamps designed to hold the rail upright. Two variations of this design were installed for permanent service in the Akashi ballasted elevated structure and the ballastless Shimo Kanzakigawa Bridge. Octave band noise and vibration level reductions are presented for the resilient rail relative to standard rail for frequencies from 63 to 8000 Hz. The level reduction on stringer web and upper flange were roughly 5 to 10 dB at 125 Hz, 0 to 10 dB at 63 Hz, and 5 to 10 dB at 250 Hz. The track design was found to be durable over one year of operation.

A-090 Braitsch, H.
Das "Kolner Ei" (Oberbau 1403/c).
(collection of articles) Verkehr und Technik, Heft 7,8,10,12 (1979) [in German].

These series of four articles compare the performance of the Clouth 1403/c rail fastener (Cologne "Egg") with floating slab track, ballast and tie track, and ballast mats. Data are presented which indicate that tunnel wall vibration levels for the Cologne Egg fastener are comparable with those for floating slabs on other rail systems. However, when compared with data collected on the same system, tunnel wall vibration levels for the Cologne Egg relative to a floating slab system are about 10 dB higher at 31.5 and 40 Hz, of comparable level at 50, 63, and 80 Hz, and 8 and 17 dB higher at 100 and 125 Hz, respectively. The Cologne Egg is compared with the earlier 1403/b version and gives similar tunnel wall vibration levels at 31.5 and 40 Hz while between 50 and 100 Hz, the Cologne Egg gives about 10 to 12 dB lower levels.

A-091 Sowry, J.A.
The railroad runs under the middle of the house...and no one knows.
(journal article) Rubber Dev, 25:4 (1972).

The vibration isolation of a large multi-story structure with 240 natural rubber and steel laminates is discussed. The building is a 310 unit hotel constructed directly above Britain's Primrose Hill tunnel through which run heavy express trains. The bearings were surrounded by 10 mm thick asbestos for fire protection. Horizontal displacement was controlled with 14 stabilizing wind braces and additional bearings. No vibration isolation performance curves are given.

A-092 Jenkins, H.H.; Stephenson, J.E.; Clayton, G.A.
The effect of track and vehicle parameters on wheel/rail vertical dynamic forces.
(journal article) Railroad Eng, 3:1,2-16 (1974).

This paper is concerned not with groundborne vibration but with failure of railroad track and vehicle components. The brunt of the paper concerns the vertical wheel/rail forces produced at a rail joint. However, the frequency range discussed includes the range of groundborne noise and vibration. Measurement data are presented which show significantly lower forces and accelerations with SAB resilient wheels than with standard solid wheels for frequencies above 30 Hz, as illustrated by spectral density plots. The reductions of some frequency components were on the order of 10 to 20 dB. Approximate methods for calculation of forces and Hertzian contact stresses are presented in the appendix. The main causes of increases in the vertical force between wheel and rail are concluded to be: isolated irregularities, e.g., joints, welds, points and crossings; periodic irregularities, e.g., due to corrugations, sleeper spacings; random variations of longitudinal profile; vehicle defects, e.g., wheel flats and eccentricity; random variations of sleeper support stiffness. Theory and computer programs have been developed.

A-093 Lubliner, J.
A model of audio-frequency vibration of buildings.
(journal article) J Sound Vibr, 68:3,335-340 (1980).

A model is presented for prediction of vibration attenuation in multi-story buildings. The transmission and attenuation depend on the relative tuning of neighboring columns. An approximate relation between the percentage variations, U, of resonance frequencies from a story to story; the attenuation a, in decibels; and the number of stories, n, is presented as:

$$a = C \sqrt{U/n}$$

where C is a constant equal to about 17.5. This formula is based on extensive numerical computations using a multi-degree-of-freedom model for generalized bending and shear modal vibration.

A-094 Hehenberger, W.
Choosing the right track for urban conditions.
(journal article) Developing Railways (1975)
[issue unknown].

The author discusses the economic, installation, and environmental aspects of various track support designs. Track supports are arranged under the following headings:

- Basic ballast and tie

- Elastomer under rail foot
    - Normal pad
    - Special insert

- Elastically supported baseplates
    - With lateral stops
    - Relying on shear in bolts
    - Vulcanized (bonded) without preload.

Theoretical work by Steinbeisser and the author are cited which lead to the following partial list of conclusions:

- Too high a specific loading of fastener inserts can increase vibration forces by up to 50 percent.

- Alteration of fastener damping has no appreciable effect on fastener forces.

- A favorable effect arises from an increase of the fastener spacing and a reduction of rail bending stiffness.

- An alteration of the mass of the wheel-set causes no appreciable change in vibration forces.

- The danger of groundborne noise nuisance in nearby buildings is indicated to be greater in heavy ground (such as clay) and if the tunnel lies below the water table.

A-095 Daligadu, D.
Howard Park Area-Streetcar Vibration Investigation-Measurement Results-26 High Park Gardens-New Rail Installation.
(report) Toronto Transit Commission, Research Memo #489A (1977).

This research memo is a continuation of Reference A-104. Daligadu's memo is primarily concerned with the effect of installing new rail at a section of track opposite 26 High Park Gardens on the groundborne vibration and noise at the curb and inside the residence. Vibration acceleration data are presented in terms of 1/3 octave band spectra, along with tables of overall vibration. The result of the test is that very little difference in the groundborne vibration spectra or amplitudes were observed between the new and old rail. However, significantly greater differences appeared between individual PCC streetcars and operation at different train speeds. The data are compared with a third set of measurement data, collected on Bathhurst Street, which indicate substantially lower vibration levels (by about 10 to 20 dB) than were recorded at the first two test sites, on High Park Gardens and Howard Park Avenue. However, the nature of the differences suggests a possible attenuator error. The results of these tests and subsequent tests are discussed in much greater detail in Research Memos #489, #484, and #499. See references A-104, 114, 119.

A-096 Paulson, J.N.; Silver, M.L.; Belytschko, T.B.
Dynamic Three-Dimensional Finite Element Analysis of Steel Transportation Structures.
(final report) University of Illinois. Department of Materials Engineering, Chicago, IL. for: U.S. Department of Transportation, DOT-TST-76-46 (1975).

The report presents a detailed finite element analysis model for steel aerial structures, including analysis of the results. Of particular interest for groundborne noise and vibration are the vibration spectra predicted for the support columns, which show strong peaks at about 40 Hz. Most of the analysis is concerned with vibration at other points on the structure. Soil/structure interaction is not discussed.

A-097 Park, T.; Silver, M.L.
Dynamic Soil Properties Required to Predict the Dynamic Behavior of Elevated Transportation Structures.
(interim report) University of Illinois. Department of Materials Engineering, Chicago, IL. for: U.S. Department of Transportation, DOT-TST-75-44 (1975).

This report describes a number of dynamic testing procedures for determining the compression and shear moduli of wet and dry sands, as well as their material damping properties. Although the discussion refers often to the effects of these parameters on the dynamic motion of aerial structures and on vibration propagation within soil, little or no direct relation between test results and ground vibration problems are indicated. However, many detailed test results are included, together with a detailed discussion of the test methods. The methods considered include:

- Cyclic simple shear
- Dynamic triaxial
- Resonant column
- Staged testing (successively incremented load).

The analysis and discussion of dynamic triaxial test results include:

- Behavior of dry sands during strain-controlled cyclic loading.

- Behavior of saturated sands during strain-controlled undrained cyclic triaxial loading tests.

- Volume change behavior during dynamic stage testing.

- Comparison of fresh and stage tested specimens.

- Comparison between results of triaxial and simple shear tests for dry sands.

No groundborne vibration data are presented for comparison with these test results.

A-098 Nelson, J.T.; Saurenman, H.J.; Wilson, G.P.
Metrorail Operational Sound Level Measurements: Groundborne Vibration and Noise Levels.
(preliminary report) Wilson, Ihrig & Associates, Inc.
for: Washington Metropolitan Area Transit Authority (1979).

This report describes the measurements, analysis, and results of a general survey of groundborne vibration for train operation in subways and on at-grade ballast and tie track. The subway constructions include:

- Soil-based concrete double box subway
- Soil- and rock-based circular concrete cast-in-place tunnels
- Soil-based circular steel tunnels
- Rock-based horseshoe tunnels.

The authors evaluate the vibration reduction of floating slabs, both in the soil-based double box and in circular concrete tunnels. Measured vibration levels are compared with predictions, with the result that predicted levels are generally higher than measured.

A major conclusion of the report is that below 50 Hz groundborne vibration from rock-based tunnels can be 10 to 20 dB lower than from soil-based tunnels. Groundborne vibration from circular soil-based tunnels can also be 10 to 20 dB higher than for double box subways above 50 Hz. Groundborne vibration levels from ballast and tie track can also have significantly higher levels than does vibration from subway structures. The floating slab trackbeds perform as damped, single-degree-of-freedom spring-mass systems. A prominent peak in the 1/3 octave band spectrum at about 20 to 25 Hz for groundborne vibration is tentatively identified with the primary stiffness of the vehicle trucks. The frequency range of analysis extends from 3.15 Hz to 630 Hz or higher, and data are included for the distances between measurement points and the subway structure, as well as for depths of the structures. Measurements of groundborne vibration on building structures and comparisons between levels from line track and special trackwork are also included. The results of this report are many and varied and represent some of the most up-to-date data on groundborne vibration from modern U. S. transit systems.

A-099 Anonymous
Draft Standard Method for the Measurement of Vibrations in Buildings Adjacent to Railway Tunnels and Tracks-Test Code for...Underground Tunnels.
(report) UITP International Metropolitan Railways Working Group on Measurement of Noise and Vibration (unpublished minutes), International Union for Public Transport (date uncertain).

This committee has worked out tentative test code for measurement of tunnel structure vibration. The subjects in the report include:

- Scope
- Nature of tests
- Quantities measured
- Measuring apparatus
- Background level
- Track conditions
- Test trains
- Location of transducers
- Procedure
- Presentation of results.

A summary of comments is also included.

The highlights of the tentative code are:

- Measurement results should be presented in terms of vibration velocity level in dB re 10^{-8} m/sec.

- Vertical and transverse vibration should be measured at the invert between the rails and between the ties or fasteners, at the tunnel wall 1.2 m above the top-of-rail and possibly on the rail web.

- Additional transducer arrays should be located at 20 m to either side of the primary array for comprehensive testing.

- Three train passbys are needed at each of the test train speeds.

- Train speeds should be 40 km/hr for tramways, 60 km/hr for subways, 80 km/hr for express traffic, and at the maximum speed used in normal operation.

- The bandwidth should be at least 10 Hz to 1000 Hz.

- Spectra should be presented as octave band or 1/3 octave band vibration velocity level re 10^{-8} m/sec.

This proposed test code represents the first international effort for standardization of tunnel vibration measurements. Minutes of the meeting held in Milan include comments to the effect that the lower frequency limit for measurement should be extended to 3.15 Hz. The limit of 10 Hz was tentatively used because it represents the lower limit of most sound level meters.

A-100 Johnson, K.L.; Gray, G.G.
Development of corrugations on surfaces in rolling contact. (journal article) Proc Inst Mech Eng, 189:13/75,45-58 (1975).

A detailed discussion of experimental and theoretical research concerning development of corrugation due to rolling contact resonance is presented. The rolling contact resonance is determined by the Hertzian contact stiffness and masses of the contacting elements. The wavelength of corrugation is determined by the contact resonance frequency and surface contact translational velocity, e.g., rolling contact velocity. The amplitude of corrugation becomes stable after a sufficient number of passes. Of particular interest is that the stable amplitudes are much smaller for point contact than for line contact and with materials which strain-harden appreciably. For railway rails, corrugation wavelengths are on the order of 50 mm indicating a contact resonance frequency of about 500 Hz.

A-101 Lang, J.
Schallschutzmassnahmen bei der Viener U-Bahn). (Sound Isolation Measurements at the Vienna U-Bahn).
(journal article) (citation & date uncertain) [in German]

In this article, the vibration isolation performance characteristics of a variety of rail support systems are considered, as well as other problems in rapid transit noise control. Specific topics considered include: Isolif ballast mats, wood ties on rubber pads in concrete invert, and variation of ballast thickness from 20 to 80 cm.

Octave band invert vibration velocity levels, over the frequency range of 63 to 4000 Hz are presented for both wood tie and direct fixation systems. The maximum vibration levels evidently occur at 63 Hz or lower, outside the range of analysis. Wood ties on 80 cm ballast produce the lowest vibration velocity levels, while rail on rubber pads on concrete invert produce the highest. The spread is from 10 to 20 dB. Octave band vibration reduction curves are presented for the Isolif ballast mat installed at a number of locations. Generally, about 10 to 20 dB vibration reduction is indicated for octave bands of 63 Hz and higher. At 31.5 Hz, the reduction is between 0 and 10 dB.

The paper presents detailed figures for a unique track support system, consisting of a cross-tie placed on two separate longitudinally continuous concrete benches, with a resilient glass-fiber pad between the benches and the invert. The cross-tie is supported by ribbed elastomer in recesses in the concrete benches. The glass-fiber pad is 5 cm thick, weighs 120 kg/cu m and has a modulus of 2000 N/sq m.

A-102 Nolle, H.
High-frequency ground vibration measurements.
(journal article) Shock Vibr Bull, 48:4,95-103 (1978).

The mounting techniques of vibration transducers on soil surfaces form the subject of this essay. A wide variety of mounting spike designs is considered for minimizing coupled horizontal and rocking vibration, and vertical vibration. The paper gives experimental data on the upper limit of frequency response of these mounting configurations for a variety of representative soils. The general conclusion implied by these data is that even if relatively marginal contact between the spike and soil is maintained, a flat frequency response up to and above 100 Hz may be obtained for all but the loosest soils. When good contact is achieved, the response is improved substantially, to about 200 Hz. For very stiff soils, frequency responses up to 400 Hz were obtained. A second-order spring mass model is used to describe the dynamic response of the mounting assembly and is found to agree well with experimental data. Nolle discusses the application of these mounting configurations to problems of groundborne vibration from rapid transit systems. He gives representative data for ground vibration from ballast and tie track, resiliently supported concrete tie track, and floating slab track and argues that measurement transducer frequency response must be as high as possible for groundborne vibration which may contain troublesome frequency components as high as 800 Hz.

A-103 Bender, E.K.
Noise and vibration of resiliently supported track slabs.
(journal article) J Acoust Soc Amer, 55:2,259-268 (1974).

Bender analyzes the dynamic interaction between the rail and the floating slab vibration isolation system, including the effects of transverse bending modes within the floating slab. This analysis is evidently the starting point for subsequent work on the subject performed by Cambridge Collaborative. This report is primarily concerned with noise radiation by the slab. However, the net force reduction obtained by using the slab is evaluated and found to be that of a single-degree-of-freedom oscillator. The article provides considerable insight into the nature of floating slab vibration. The author calls for further work in the area of subway structure response.

A-104 Hunt, A.D.
Howard Park Streetcar Noise and Vibration Measurements. (research memo) Toronto Transit Commission, #489 and #498 (1977).

Hunt gives groundborne vibration and noise data for two residential, wood-frame structures, adjacent to the right-of-way of a PCC streetcar line. Three test vehicles were included. One was evidently in good condition, one had wheels of rough radii, and the third had a wheel with excessive runout. Of these cars, the one with the excessive runout produced the greatest groundborne noise and vibration. The vibration acceleration spectra recorded in the residential structures showed a very sharp peak at 31.5 Hz and significant vibration energy at higher frequencies in the range of 125 to 315 Hz. The spectra at both structures were remarkably similar, in spite of the fact that the houses were separated by several hundred feet and probably of dissimilar construction. Simultaneous measurements were made of vertical vibration acceleration on the floor near the wall closest to the tracks and on the sidewalk in front of each structure. The data indicate significant amplification of structure vibration at 31.5 Hz, relative to the sidewalk. A broad peak in the vibration spectrum also appears at 31.5 Hz for the sidewalk, extending as much as 20 dB above its shoulders; a second and higher peak in the acceleration spectrum occurs at about 31.5 Hz. The data are presented in terms of 1/3 octave bands, from 3.15 to 1250 Hz. Tables of overall vibration acceleration for given measurement conditions also appear. The residents' comments included in the text of the memo indicate their reaction to the vibration for given vehicle condition. See also reference A-114, A-95, A-119.

A-105 Wilson, Ihrig & Associates.
Analysis and Design Recommendations - Floating Slab Track Support Systems.
(report) Wilson, Ihrig & Associates, Oakland, CA. for: Daniel, Mann, Johnson & Mendenhall, Baltimore, MD (1976).

This report presents the general design considerations and parameters for the floating slab track support systems recommended for use on the Baltimore Region Rapid Transit System. Several possible floating slab designs are presented, all of which should reduce groundborne noise and vibration levels by 10 to 15 dB, relative to the levels with direct fixation resilient fasteners. Both continuous and discontinuous floating slabs are discussed.

A-106 Groetenhuis, P.
Floating track slab isolation for railways.
(journal article) J Sound Vibr, 51:3,443-448 (1977).

This paper presents a number of the track vibration isolation systems used in Britain. Included is a discussion of human sensitivity to vibration and a reference to Dieckmann K-values for characterizing human sensitivity to vibration in simple terms. Three floating slab designs are presented:

1. a resiliently supported bridge with constrained layer damping

2. a continuous floating slab on a bituminous damping layer and ballast and tie track, used in a box subway configuration, and

3. a continuous floating slab with direct fixation, used in circular, low cross-section tunnels.

Groetenhuis evidently believes that the continuous floating slab is preferable to the discontinuous double tie design, as used in Toronto, Canada, because in the absence of damping, bending vibration energy may be concentrated within the double tie. However, he recommends a constrained layer damping technique for the continuous floating slab, to avoid resonant vibration within the slab. An unsupported statement is included to the effect that the local build up of vibration in the slab prevents the TTC discontinuous double tie from performing adequately. A fundamental resonance frequency of 7 to 12 Hz is recommended for floating slabs. The slab mass should be as large as possible. Two long stretches of isolated slab track are in London: the oldest section is located at the Barbican Redevelopment and the other is on the extension of the Piccadilly Line to London Airport. Both are cut-and-cover subway.

A-107 Genen, J.; Chung, Y.I.
Response of a continuous guideway on equally spaced supports traversed by a moving vehicle.

(journal article) J Sound Vibr, 67:2,245-251 (1979).

An algorithm is developed to analyze the dynamic response of a continuous guideway resting on equally spaced supports being traversed by a moving vehicle. A critical speed, one at which the amplitude of the guideway displacement becomes large, is determined. The critical speed corresponds to the slowest possible speed at which a transverse wave can propagate longitudinally in the guideway structure. A parametric study is also presented.

A-108 Fields, J.M.
Railway noise and vibration annoyance in residential areas.
(journal article) J Sound Vibr, 66:3,443-458 (1979).

This paper summarizes the results of a 1975 British Railway noise study, including the results of an attitudinal survey regarding groundborne vibration from railway trains. However, no vibration measurements were performed to correlate human response with vibration levels. Instead, the human response is correlated with distance from the train right-of-way, train passby frequency, and so forth. The attitudinal survey was made by circulating a questionnaire, containing such questions as:

- Do the trains make the house, or other things, vibrate, shake, rattle, and roll?

- Are the residents at least a little annoyed?

- Is the vibration caused by the train a problem?

- Are the residents very annoyed?

The results of the survey indicate that the percentage of positive responses to the various questions was closely correlated with distance from the train right-of-way. Any of the measures of vibration annoyance are satisfactorily represented as related to the logarithm of the distance from the track. The percentage of respondents who notice things vibrating, shaking, or rattling is 80% at distances less than 25 m from the track and decreases very rapidly to 20% at 150 m. Evidently, some people at every level who notice vibration are not annoyed by it, but most people are. Of those who reported experiencing vibration, 80% actually felt it, as opposed to those who only heard windows rattle, etc. A significant percentage felt that the vibration could damage the structure.

Many factors were examined, to determine whether they are related to vibration reactions. After the effect of distance is removed, the effect of increasing train speed from 30 to 150 km/hr increases the percentage of those who said that vibration was a problem by about 15 to 20%. Reactions to vibration appear not to be seriously affected by the number of trains per day. However, about 75% of the respondents could distinguish between train types. The visibility of the railway increases the reaction to vibration by about 6%, among those who consider the vibration a problem. The tendency for the proportion of trains at night to increase reactions to vibrations is very weak and probably statistically insignificant.

A-109 Wilson, G.P.
Groundborne Vibration and Noise Measurements and Analysis-309 Sycamore Street.
(letter report) Wilson, Ihrig & Associates, Inc. for: Metropolitan Atlanta Rapid Transit Authority, Atlanta, GA (1980) [proprietary information].

Vibration measurements were conducted at a residential structure at 309 Sycamore Street, Atlanta, Georgia, located approximately 80 to 100 ft from a double box subway structure with discontinuous double tie floating slab track vibration isolation. Vertical acceleration measurements were made on the floor of the first-floor front bedroom, one near the front wall of the structure and the other near the center of an interior wall. Noise measurements were also taken, at a location between the vibration measurements and away from the walls or floor. Data from the two vibration measurement locations allow investigation of the effect of structural resonances on the vibration amplitude. The vibration data are presented as 1/3 octave band spectra, for a frequency range of 3.15 to 1250 Hz. One-third octave noise level data are shown for the frequency range of 12.5 to 5000 Hz. The range of maximum 1/3 octave band vibration extends from 10 to 25 Hz. This is characteristic of vibration from systems with floating slab vibration isolation. However, a peak at 25 Hz is evident for westbound trains, though not for eastbound trains; this peak is of a magnitude similar to the peak at 16 Hz which may be attributed to the floating slab resonance and the resonance of the primary suspension of the trucks. The difference in magnitude between vibration from eastbound trains and westbound trains is about 5 to 10 dB and is particularly noticeable for data recorded at the outer wall. The levels for the westbound trains are higher even though the westbound track is farther from the measurement location than the eastbound track. Some of this difference can be attributed to differences in train speeds. The 1/3 octave noise is concentrated below 25 Hz and is lower than would have been expected on the basis of the vibration data alone.

A-110 Meachum, H.C.; Prause, R.H.; Waddell, J.D.
Assessment of Design Tools and Criteria for Urban Rail Track Structures. Vol 2: At-Grade Slab Track.
(final report) Battelle-Columbus Laboratories, Columbus, OH, DOT-TSC-UMTA-74-5. for: U.S. DOT; Transportation Systems Center, DOT-TSC-563. avail: U.S. DOT; Urban Mass Transportation Administration, UMTA-MA-06-0025-74-4 (1974).

This report presents the results of a program to review the technical factors which govern the design and performance of at-grade urban rail track structures. Volume I gives results related to the design and performance of ballast and tie track construction, and Volume II is an evaluation of the technical requirements for designing track constructed from concrete slab. The reports are concerned primarily with design loads, deflection, lateral strength, and maintenance. There are a few passing references to groundborne noise and vibration, but the information is neither original nor complete. The appendices contain discussions on estimating tie deflection, ballast pressure, a ballast pyramid model, soil classification, and track structure settlement. Rail corrugation is discussed in section 4.6 and rail fasteners in section 4.5.

A-111 Verhas, H.P.
Measurement and Analysis of Train Induced Ground Vibration.
(thesis) University of Southampton, Southampton, England (1977).

A relatively detailed analysis of groundborne vibration measured at Hathern Station and Blisworth in London for at-grade railway trains is presented. Vibration spectra, the transfer function (or frequency response) of the soil, and the vibration propagation velocity for the soil were measured.

The velocity of propagation was measured by cross-correlation of vibration signals, giving 184 m/sec at the frequencies of 14 Hz and 70 Hz. This surprising agreement over such a large frequency range indicates that the same basic mechanisms are involved at low and at high frequencies. The observed propagation velocity is identified with that of shear waves and/or Rayleigh waves in the soil. The author identifies the train wheel passby frequency as most significant in the frequency ranges of 12 to 18 Hz and sleeper spacing as most important at 45 to 65 Hz. Frequency shifting within these ranges is attributed to variation in train speed and to the Doppler effect. Overall vibration levels do not change with train speed. Damping in the soil is found to increase linearly with frequency. Finally, these measurement techniques included the use of plates embedded in plaster and set in the soil. The frequency response of the transducer mounting was evaluated by striking the transducer and recording simultaneously the exciting force and the responding velocity. The transducer and mounting exhibited a resonance at about 465 Hz and was therefore judged to be very good.

A-112 Nayak, P.R.; Tanner, R.B.
Frictional and Vibratory Behavior of Rolling and Sliding Contacts.
(report) Bolt, Beranek & Newman, Inc., Cambridge, MA, BBN-2402. for: U.S. DOT; Federal Railroad Administration, FRA-RT-73-13. avail: U.S. National Technical Information Service, PB-214-939 (1972).

Experimental and theoretical investigations of the influence of rolling velocity, normal load, and high-frequency normal vibration on the traction/slip characteristics of rolling discs are described. Of greatest significance to concerns of groundborne noise and vibration is an analysis of the high-frequency dynamic response of rolling bodies to surface irregularities, specifically that of two rolling discs and of a wheel on a rail. Questions of loss of contact, plastic deformation, and rail corrugations are discussed. The report provides theoretical data concerning the influence of Hertzian contact stresses on the dynamic forces between the wheel and rail. The relationship is essentially nonlinear, but linearizing approximations are introduced for various frequency regimes. But the analysis focuses on the frequency range above 100 Hz. At lower frequencies, the Hertzian relative displacement between the wheel and rail is apparently less significant than the displacements due to rigid body motion of the wheels or bending of the rail. The frequency at which the Hertzian contact stresses and displacements become important for estimation of dynamic wheel/rail forces is simply that of the rail/fastener resonance. Finally, the wavelength of corrugations is directly related to the contact resonance frequency and rolling velocity. Based on the above, Hertzian contact stresses may not be particularly important in the generation of groundborne vibration below about 100 Hz.

A-113 Hurst, D.R.
Sound and Vibration Frequency Analysis.
(technical report) Toronto Transit Commission, Ontario, Canada (1976).

This report describes the 1/3 octave real time analysis system used by the Toronto Transit Commission to analyze groundborne vibration and noise. The system uses custom battery-operated instruments constructed by WIA, a Nagra IV SJ scientific tape recorder, a B & K 2131 1/3 octave band real time analyzer, B & K 2307 level recorder, a Tektronix type 31 programmable calculator, and a number of other instruments. Examples of plotted 1/3 octave and octave band vibration data are included.

A-114 Hunt, A.D.
Streetcar Vibration Survey - Summary.
(research memo) Toronto Transit Commission #499
(1977).

This memo is a summary of the results of measurements described in Research Memos #489, #489A, #484, and #498 (references A-95, A-104). All of the data presented in this memo refer to vibration at the sidewalk, approximately 15 ft, 6 in. from various streetcar tracks. The speed of the streetcars are about 22 mph.

Hunt concludes that vibration levels can vary considerably; any of the following conditions can change them:

- Streetcar speed
- Streetcar wheel conditions
- Trackbed design
- Track condition
- Track type
- Distance from track
- Adjacent soil strata
- Building condition.

The 1/3 octave spectra presented indicate a very significant frequency peak at 31.5 Hz, which does not change significantly with train speed, train type, or location. This may indicate a strong resonance present in the truck. Low-frequency vibration, below 50 Hz, rises substantially with train speed. At higher frequencies, the change in vibration level with speed is more erratic, but it rises with increasing speed. Very significant differences are indicated between various cars at the same locations, indicating that differences between the cars may have the greatest effect on vibration, perhaps more than trackbed design or train speed.

A-115 Martin, J.F.
Dynamic Load Test of Support Pads for TTC. Dynamic Load Test of Support Pads with Shims.
(academic report) University of Waterloo Research Institute. for: Toronto Transit Commission (1975).

This report describes the dynamic testing procedure for evaluating the floating double tie support pads used on the TTC (Toronto) system. The load-deflection curves for compression and shear recorded at .03 Hz are of particular interest. Unfortunately, load-deflection curves at higher frequencies are not given, so that estimates of damping cannot be made from this report.

A-116 Hannelius, L.
Vibrationer fran tung tagtrafik. (Vibrations from Heavy Rail Traffic).
(report) Swedish State Railways, Geotechnical Department (1978) [in Swedish].

This report presents a detailed study of overall vibration velocity and acceleration magnitude, recorded at various distances from at-grade railway track and at the foundations and upper floors of building structures. Unfortunately, the entire text is in Swedish, although the figures are captioned in English. Most of the data are taken from strip-chart recordings. The frequency spectra presented are in the form of photographs of the display of a constant bandwidth analyzer. The frequency range extends either from 0 to 20 Hz or from 0 to 200 Hz.

Rayleigh waves are indicated as most significant. However, in the presence of bedrock, reflections of body waves can also be important. Most of the strip-chart records clearly indicate a decrease in magnitude of ground vibration with depth below the surface. This decrease implies Rayleigh wave propagation. These data accord with conclusions reached by Verhas (Reference A-111), regarding groundborne vibration from surface trains. The use of sheetpiling to reduce vibration is discussed and is effective for clay soils. The dominant frequency range of vibration velocity is in the neighborhood of 5 to 10 Hz. If the railway rests on a pile of foundation, groundborne vibration is reduced substantially, perhaps due to the increased impedance provided by the piles, which are supported on stiffer soils. Finally, upper-story horizontal wall vibration is indicated as typically around 10 dB higher than vertical foundation vibration.

A-117 Blejwas, T.E.; Feng, C.C.; Ayre, R.S.
Dynamic interaction of moving vehicles and structures.
(journal article) J Sound Vibr, 67:4,513-521 (1979).

This article describes a procedure, developed to stimulate the dynamic interaction between traversing vehicles and structures. The authors employed Lagrange multipliers in the time domain to satisfy constraint conditions between the systems. Illustrative examples are presented. The results compare well with analytical and experimental results and demonstrate the importance of terms that are often overlooked in the constraint equations. One such oversight is the lack of contact between the vehicle wheels and the roadbed.

A-118 Braitsch, H.
Eggs laid in Koln soften track noise.
(journal article) Railway Gaz Int, December 1979,11-15 (1979).

This short article describes a unique rail fastener design developed by Clouth of Germany. The fastener has been installed on the Cologne U-Bahn as a noise control device. The fastener uses an elliptically shaped elastomer in a shear collar, which provides relatively low vertical stiffness but high lateral stiffness. Stiffness values were not given. The total height of the fastener is 90 mm, although lower profile designs are being considered. The fastener has been dubbed the Cologne Egg.

The vibration reduction performance of this fastener seems comparable to that of several floating slab systems, except that the equivalent resonant frequency is about 40 Hz, rather than 20 Hz. The vibration reduction, relative to standard ballast and tie or to ballast and tie with ballast mat, are given as 10 to 15 dB at frequencies up to about 40 Hz and 25 dB at frequencies between 50 and 80 Hz. The reduction at low frequencies is obviously open to question, but the absolute levels obtained with the design compare reasonably with those obtained with floating slab track. The data are evidently based on measurements performed at the tunnel wall. The most important feature of the fastener design is that the installation cost (1550 DM/m) is a fraction of that of the floating slab track (2620 to 3125 DM/m). Additional data regarding this fastener design are needed; it is an obvious candidate for testing in the United States.

A-119 Daligadu, D.; Powell, J.K.
Howard Park Area: Streetcar Vibration Investigation-Various Measurement Results.
(research memo) Toronto Transit Commission, #498/489A/484 (1978).

This memo is a continuation of Research Memos #489 and #489A, on groundborne noise and vibration from streetcars. Additional measurements were taken to evaluate the effect of various trackbed designs on the vibration. Vibration data are presented through tables of vibration levels and 1/3 octave band spectra, representing streetcar speeds of 10 and 25 mph. The various trackbed designs include:

- New rail vs. old rail
- Granite sets vs. concrete track surface
- Asphalt track surface
- Concrete track surface
- Granite sets track surface.

Research Memo #499 (Reference A-114) generally summarizes the results of these tests.

A-120 Splittberger, H.
Uber Die Erschutterungs-Immissionen... (On vibration immissions by road and rail traffic).
(journal article) Intl Verkehrswesen, 27:5,245-248 (1975) [in German].

The emissions and immissions of vibrations should be taken into account in the planning stage of new transport undertakings. If this is not done and large vibrations appear, it is then very difficult to find remedies. Discussion includes criteria, standards, human response, and measurement results for both road and rail traffic.

A-121 Isaeev, I.K.
Kompensatsiya Akusticheskovo... (Reduction of acoustic field caused in soil by running railway trains).
(journal article) Vestnik (Vnttzt), 35:2,40-43 (1976) [in Russian].

Theory of wave propagation is partly given. The rolling stock creates cylindrical waves in soil which can be resolved into plane waves. Considering an upper layer, it is shown that the square module of the complex coefficient of reflection is practically constant. The diffraction problem with a slit in the ground is also considered. It is concluded that a plane fissure in the ground between receiver of a wave and the railway track reduces the power of the wave passing the fissure by 10 log (W1/W2) which is of the order of 30 dB, where W1 = incoming wave power, W2 = received wave power. This covers a wide range of frequencies. This conclusion may be extended to shallow underground tunnels and to motorways.

A-122 Dolling, H.J.
Die Abschirmung von Erschutterungen durch Bodenschlitze. (Shielding against vibrations by trenches in the soil, Part 1).
(journal article) Bautechnik, 5,151-158 (1970) [in German].

Theory of wave propagation in an elastic half-space excited vertically is given. Rayleigh wave and the action of a trench is investigated using energy balance methods.

Systematic tests were carried out at excitation frequencies between 10 and 100 Hz with variation of parameters, especially trench depth and length. Measurements were taken at the surface and inside a building. Test results are compared with theory.

A-123 Konchin, G.G.
Isledovaniye kolebanyi grunta... (Vibrations on slopes of railway embankments).

(journal article) Vestnik, 1974:6,42-45 (1974) [in Russian].

Some vibration measurements are given. It is concluded that with ballast extending down the slope that the vibration velocity increases with train speed. The vibration velocity is greater for concrete than for wood sleepers, greater opposite the rail joints, and greater for horizontal perpendicular to track than for vertical vibrations. Observed frequencies may be up to 120 Hz, however, the main frequencies are 25 to 75 Hz. The main frequency depends on type of sleeper and on ballast thickness (a change from 20 cm to 100 cm thickness decreased the main frequency by 11-28%) but is independent of train speed (from 55 to 135 km/hr).

A-124 Konchin, G.G.
Spektralnyi Sostaw... (Spectrum of propagating vibratons on track bed and embankment).
(journal article) Vestnik, 1977:4,39-43 (1977) [in Russian].

Triaxial measurements of vibration (train speed 65 to 70 km/hr) were taken under rails. The vertical vibrations were higher than the horizontal (Vy and Vx). The mean values of Vy and Vx were approximately half of the mean of Vz. The authors concluded that: the ground vibrations are effectively filtered by ballast and at a distance of 4 m from track axis, there are practically no vibrations at frequencies higher than 120-140 Hz. This investigation could be a starting point for laboratory and then in-situ research work on stability of the ground under the influence of vibrations.

A-125 Kaess, G.; Stretz, R.
Stand Der Erprobung... (The present position as regards

experience with elastic mats under ballast).
(journal article) Eisenbahntechnische Rundshau, 28,671-680 (1979) [in German].

This paper gives test results of bridge installations utilizing ballast mats. Preliminary conclusions are that it is not necessary to use mats in general but there may be cases of existing noisy bridges where the mats can help. As regards to new structures, bridges, and tunnels, no conclusions have been reached because the tests are in progress.

A-126 Keim, D.
Synthetic materials in track.
(journal article) Der Eisenbahn Ingeunieur, 1978: February, 60-68; 1978: March,122-135 (1978) [in German].

This two-part paper deals with methods to improve drainage, to prevent ingress of water from the ground, to improve thermal insulation on sections likely to be disturbed by frost, to improve tunnel waterproofing, and to increase the elasticity of ballasted track laid on hard foundations by placing polyurethane (PUR) mats under ballast. Also discussed is the use of PUR to bind and stabilize ballast, and its use in ballastless track to improve load distribution and to reduce noise and vibration. Also discussed is the case of Celasto (PUR) under rails, with Ultradur (PTB) and Lupolen (PE). The Lupolen is used for height adjustment. Other trade products discussed are Ultramid and Palatal. Technical data on Lupolen and Cellasto include compression strength, elastic modulus, and shore hardness. The use of adhesives and sound absorption are also discussed.

A-127 Birmann, F.
Track parameters, static and dynamic.

(journal article) Proc Inst Mech Eng, 180:part 3F (1965).

This paper is about tracks in the open on soft soil and loose ballast and on rock with consolidated bedding. The oscillating mass of track will differ in behavior depending on construction, rail profile, sleeper (tie) spacing, etc. The damping and phase shifts are mentioned and a few values are given. Natural frequencies of track with and without load are calculated and measured for wooden and concrete sleepers. Lateral elasticity is also discussed.

A-128 Makowski, J.
Analysis of the mathematical model of the railway track formation.
(journal article) Rail Intl, 1980:March, 152-185 (1980).

The distortion in track formation and embankment, and methods of calculating the stability of railway embankments, are covered. Mathematical models are presented that describe the dynamic stressing of track and the atmospheric factors, particularly water and temperature, on track formation. The article includes a table of frequencies and amplitudes of vibrations for the different calculations. Some conclusions from the research of the Krakov group on propagation of vibration in dry ground caused by rolling stock are: no obvious relationship was found between the values of vibration amplitude and speed over the range of 20 to 60 km/hr; and within a distance of 10 meters (on straight section), no relationship was found between amplitude and distance from the passing train. Various track stiffnesses are defined, formulas for dynamic load increments are given, a vehicle track model is given, and many formulas deduced, e.g., ratio of amplitude of the forced vibrations of the track to the amplitude of the track irregularities.

A-129 Funke, H.
Unebenheiten... (Irregularities of rail top).
(journal article) Signal und Schiene, nos.139-140, (vol and date uncertain) [in German].

Vertical accelerations for corrugations and waves are given based on theoretical calculations. The harmful effects of the irregularities include: rail defects get worse more quickly; there is an increase in the rate of fatigue failure; the track errors, especially longitudinal profile and twist get worse; rail fastenings are affected and the elastic components of the fastening will be destroyed sooner; there is an additional fatigue factor in rolling stock; the "noise load" on passengers and residents is increased; groundborne vibrations can be transmitted to nearby residents; and the energy to drive trains is increased. The wave irregularities can be reduced by grinding rails.

A-130 Keim, D.
Theoretische Untersuchungen... (Theoretical investigations of natural frequencies and vibration amplitudes of ballastless track).
(journal article) Eisenbahntechnische Rundshau, 25:1/2,94-105 (1976) [in German].

Excitations causing vibrations are due to deflection of rail under wheel load, small eccentricities and wear roughness of wheels, rail roughness, oscillations of wheels, and bending oscillations of axles, etc. Other masses can be ignored, e.g., bogie and body masses; the natural frequencies being below 10 Hz, they can be considered uncoupled. The frequencies produced by traveling train have been found by various investigators to be in the ranges of 40 to 80 Hz (up to 500 Hz), 40 to 60 Hz, and 50 to 80 Hz, therefore a rail support should not have natural frequencies within these ranges.

Data on Cellasto, a cellular polyurethane elastomer, are given. This material has been used (among other vehicle and track applications) in ballastless transverse sleeper type of track. Full data and results of calculations including natural frequencies are given in an extensive table.

A-131 Barabochin, V.F.; Lysyuk, V.C.
Uluchshineniye... (Improvement of vibration properties of track with reinforced concrete (RC) sleepers).
(journal article) Vestnik, 1980:1,48-51 (1980) [in Russian].

The conclusions include:

- Pads between reinforced concrete sleepers and ballast (over about 1 m at each end of sleeper) have a considerable effect. With plastic pads 10 and 20 mm thick, the stiffness decreases 2.0 to 3.1 times for static load and 1.7 to 1.9 times for dynamic load whereas with wood pads, 1.3 and 1.2 times respectively. Stiffness with wood pads is near that of track with wood sleepers and with plastic pads, it is smaller.

- The ballast vibration can be considerably decreased by use of pads.

A-132 Anonymous
Paved concrete rail track system for vibrationally sensitive areas - VIPACT.

(report) British Rail Research, Mk-Pub-6 (date uncertain).

This report describes the development of a new form of resilient support for a floating slab which overcomes some objections to the current alternative systems. The major advantages of the new system are the ability to adjust in situ the resonance frequency and support height as well as allowing for the support elements to be easily replaced.

The continuous floating slab is believed more desirable than the discontinuous precast slab because of energy dispersion or radiation or damping in the continuous slab which avoids buildup of local vibration energy. This has not been shown to be a real problem.

A-133 Anonymous
Tracks for railways in tunnels.
(report) British Rail Research, Mr-Pub-5 (1979).

Track systems in tunnels are usually a compromise between first cost, subsequent maintenance costs, operating noise levels, transmission of traffic generated vibrations into the surrounding ground and adjacent structures, and compatibility with rolling stock. This research note compares the respective contribution of the main types of track constructions to each of the above features and then evaluates in more detail the possible relative noise generation and vibration transmission of each type of construction and possible alternative means of improving the noise and vibration environment. The types of track discussed include ballasted track on tunnel invert, paved concrete track, concrete based track with resiliently mounted twin block sleepers (STEDEF), and track on resiliently mounted slab.

A-134 Barabochin, V.F.; Ananev, N.I.
Vibratsii Podrelsovykh... (Vibrations of supports under rails at rail joints).
(journal article) Vestnik, 1975: 6,42-47 (1975) [in Russian].

This article deals with the effects of changing from wood to reinforced concrete sleepers (ties). It is concluded that wood sleepers are a better protection against high vibrations in ballast than the concrete sleepers. The performance of concrete sleepers can be improved with elastic pads.

A-135 Raquet, E.; Tacke, G.
Sound emission of railway wheels and tests on noise-damped wheels for long distance and local rail traffic.
(conference paper) presented at 6th International Wheel Set Congress, Chicago, IL (1978).

Predominant modes of vibration and frequencies of wheels were found, and resonant absorbers were developed whose natural frequencies are tuned to the wheel frequencies to be eliminated and which have a high internal damping. There are two main designs: for long distance traffic and for local traffic. In each design, the absorber consists of several resonance blades. The blades vibrating in resonance dissipate the energy into the damping material. The absorber pads have a wideband effect over the audible range. Although no rail or track vibration tests are given, it is likely that reduction in wheel accelerations is reflected in corresponding reductions in rail accelerations.

A-136 Ungar, E.E.; Bender, E.K.
Guidelines for the Preliminary Estimation of Vibrations and Noise in Buildings Near Subways.

(report) Bolt, Beranek & Newman, Inc., BBN-2500B. for: New York City Transit Authority (1973).

Methods are presented predicting groundborne noise and vibration in buildings caused by passing subway trains. Topics include tunnel vibration; propagation through the ground; effects of intervening layers and interfaces; effects of tunnel, track, and vehicle parameters; sound radiation in rooms of long and short wavelengths; noise and vibration in below and above surface rooms; and criteria. The report presents the most detailed description available concerning the prediction procedures developed by Ungar and Bender. These procedures are also described in a later paper (A-2).

A-137 Anonymous
Vibration Study.
(report) appendix to: Structural Design Principles of Station Block Foundations. Lowe & Rodin Consultants, London. for: Crown Estate Commissioners, London, England (date uncertain).

This study was undertaken to assess the structureborne vibration and resulting noise inside two proposed buildings above and adjacent to the London Transport's Victoria Line. The building of major concern is proposed to be eight stories high with two basements and will be located above the Pimlico Station. The other building is to be three stories high with one basement and further from the subway. The subway tunnel is about 15 m (150 ft) below the ground level and about 9.5 m (30 ft) below the basement floor.

The study examines the sway of the buildings, vertical motion of the buildings, effects on the buildings' windows, and effects on the buildings' floors. Assessments are made based on the displacement amplitude measured on the wall of the ticket office of the Pimlico Station along with various assumptions and formulas which are given in the study. Although the reverberant noise levels calculated at 32 Hz are greater than that predicted using other formulas (from other sources), the conclusion was that the only possible problem could be with floor vibration at about 30 Hz.

Lowe and Rodin concluded that there was an extremely small risk of inconvenience due to vibration in the eight-story building and an even smaller risk to users of the low rise building, that anti-vibration mountings were unnecessary and that vibration should be monitored during constructon. In case of trouble, damping should be used against noise and vibration intrusion, e.g., neoprene strips at the false floor batten.

A-138 Rucker, W.
Auswirkungen von... (Effect of underground railway vibrations on planned buildings).
(journal article) Die Bautechnik, 1978:7,218-226 (1978) [in German].

This study was undertaken to determine the potential effects on new houses to be built near an underground railway line in Berlin. Vibration measurements were taken at 2, 10, 20, and 30 meters from the tunnel. Theoretical calculations were also made and indicated good correlation between measured and calculated levels. It was shown that the excitation is 0-150 Hz, and the critical frequencies are 10-20 Hz. Also, the excitation amplitudes in the ground near the building show virtually no reduction until 15-20 meters from the source.

A-139 Keim, D.; Kohler, K.A.
Verbesserung des Schotteroberbaus in Tunneln. (Improved

settings for ballasted tracks in tunnels).
(journal article) Eisenbahntechnische Rundshau, No. 59,545-548 (1978) [in German].

This paper discusses the favorable effects of utilizing the Sylomer ballast mat in tunnels for reducing structureborne noise. It also describes the properties of the mat and various laboratory and practical test results.

A-140 Latsch, P.
Zusammenhang Swischen... (Relation between stiffness of track and that of rail support).
(journal article) Eisenbahntechnik, 24:5,215-217 (1976) [in German].

Equations and sample calculations are given which show the relationship between track stiffness and rail support stiffness.

A-141 Beer, R. et al
Vertical concurrent forces between wheel and rail on crossing rail joints.
(journal article) Railway Res Eng News, Sec G, Translation Ser 79/G/3, February 1971, 62-66. Bureau Spoorwegdocumentatie, I. Limburg, The Netherlands (1971) [from Zheleznod. Transp.].

Mathematical theory and computer calculations are used to determine the forces for a passenger train coach crossing rail joints.

A-142 Kogan, A.
Characteristic oscillations and stability of rails.
(journal article) Railway Res and Eng News,

Section D, Translation series no. 71/D/7-1971. Bureau Spoorwegdocumentatie, I. Limburg, The Netherlands (1970) [from Vestnik Tsnii (sic)].

Utilizing a theoretical basis with an exterior force changing sinusoidally at train speed, the conditions of stability are deduced and the characteristic frequencies of the rail are determined.

A-143 Alias, J. et al
Treatment of surface defects in rails.
(journal article) French Railway Techniques, 1979:1,15-32 (1979).

This is a collection of several articles, each of which is briefly discussed.

J. Alias classifies defects into long (greater than 5 m) and short (between a few centimeters to 5 m); random (shelling, wheel slip marks), periodic (hollow welds), and quasi-sinusoidal called corrugations. Two kinds of corrugations are defined, 3 to 8 cm, and 1.5 to 2 meters in France. The frequency of corrugated rail vibrations as function of speed is shown.

F. Colson explains under "Reprofiling rails on the track," rail grinding procedures, the development of the Speno grinding train (consisting of five cars with 48 grinding units working at speeds of 5 to 7 km/hr running at 80 km/hr) and gives results including amplitudes of a 1.7 m defect before and after 12 passes, acoustic (in bogies) and vibration (on axle boxes) levels before and after. Also, the economics of the use of the train are discussed. F. Colson describes in "The detection and measurement of corrugational wear using a dynamic method" Car SM125, a former CFD railcar equipped by the Speno Company with complex apparatus for detection, measurement, and recording of rail corrugations. The apparatus measures noise, maximum amplitude of left and right rails, and wavelength. J.P. Fortin and I. Fourcade describe in "The measurement of short wavelength defects by a geometrical method," the principle of measurement of short wavelength rail defects, give a mathematical explanation of how to obtain a true profile from the measurements, indicate when to apply Fourier transformation, and how to deal (mathematically) with very short corrugational defects, and describe the design of the apparatus and what its main parts are. They conclude that there are now efficient methods for inspecting limiting defects. In an effort to reduce running noise and vibration, there is a reduction of fatigue effects in track and in rolling stock. Establishing the economic optimum will require more study.

A-144 Girard, J.
Etude...pour la construction des batiments...ou routiere.
(Study of measures for construction of buildings near or above railways or roads.)
(journal article) Appl Acoust, 5: 2,91-117 (1972) [in French].

A brief review is given of some antivibration mountings of track and buildings including Barbican track and Petty France building on rubber blocks over London Transports St. James' Station. A theoretical study is described in which it is assumed all points of foundation of a building move at equal amplitude and phase and that the masses are concentrated and joined by springs and dashpots. A computer program allows the calculation of amplitude of vibration velocity at any point of the chain, ratios of these amplitudes, power spectral density

(PSD) at any point as a function of the PSD at entry, and overall level at any point for any given spectrum applied at the entry. A numerical example is given for an 11-story imaginary building, with the tunnel of the metro at about the level of the basement. Theory and equipment are described for measurement of the dynamic properties of antivibration mountings under high static pressures in the 15-600 Hz band. Test results are given for four types of mountings.

A-145 Kuchlbauer, S.
Eisenbahnoberbau... (Railway tracks in tunnel).
(journal article) Eisenbahningenieur, 1978,512-520 (1978).

The ballastless tracks are described in this article mainly for engineers interested in electrification of railway lines which requires provision of catenaries in tunnels and therefore more height between the floor and crown of the tunnel. Photographs and sketches show construction of DB, Sanyo Line, Dutch, Gelde, British Railways PACT, Zublin, and Rheda tracks. References to elastomer inserts as substitutes for ballast are made but no data on vibration are given. Height adjustments, methods of track installation, connections between ballastless track inside and ballasted track outside tunnels are discussed.

A-146 Ananev, N.I.; Barabochin, V.F.
Metodologicheskiye Osnovy... (Methodological principles of investigating track vibrations).
(journal article) Vestnik, 1979:7,46-48 (1979) [in Russian].

The purpose is to ensure a standard procedure in vibration studies by various organizations in USSR. The document covers measurement, analysis, and evaluation of results. Practice has shown that in selecting an accelerometer, the upper frequency should be some five times the upper frequency of interest and the lower frequency should be less than half the lower frequency of interest. Advice is given on amplifiers. Measurements in various track components are mentioned. The form of the registered signal depends as much on the characteristics of the measuring apparatus as on coupling of the accelerometer fixed to the investigated object. A 30 x 40 x 20 mm metal piece is fixed by means of epoxy resin to the investigated rail and sleeper. Information is given for similar measurements in ballast. Some advice on filters, oscillographs, etc. is given.

A-147 Reiher, H.; Von Soden, D.
Einfluss von Erschutterungen auf Gebaude (Effect of vibration on buildings).
(first edition), West Deutscher Verlag (1961) [in German].

Forty-eight building vibration investigations were carried out including five vibration cases due to road traffic and five due to rail traffic. Damage criteria are discussed, including mathematical discussion of vibration velocity, stress, acoustic resistance with a figure giving a boundary graph between no damage/damage zones in relative frequency and relative vibration velocity. Blast effects, vibrations caused by street traffic, and protection of buildings are also discussed. Recommendations are given for protection of foundation and upper stories.

A-148 Anonymous
British Railways Technical Notes TS2, TNTS 22 and Technical Memorandum TMTS 82.
(reports), British Railways Technical Centre, Derby, England (1974 & 1977).

The three referenced reports are TS2, "The calculation of track forces due to dipped rail joints, wheel-flats, and rail welds"; TNTS22, "Track stiffness and damping - measurements and theoretical considerations"; and TMTS82, "Approximate formulas for calculating wheel/rail forces and rail displacements at rail welds and for wheel-flats."

The above reports are relevant to the problem of track vibration but they do not contain any direct treatment of vibrations. They have been selected after perusing some 20 reports. There exist some reports on vibration and noise near track but they are few, deal with particular complaints, and in general they do not contain all information necessary for full assessment of the results.

A-149 Anonymous
Messung von Schwingungs Emmissionen. (Measurement of Vibration Emissions).
(Draft DIN Standard), DIN 45669 (1979) [in German].

This report discusses specifications of vibration measurement instrumentation and documentation of vibration displacement, velocity, or acceleration. Block diagrams and formulas are given for calculation of effective values. The equipment should be capable of evaluating building vibration and providing data which may be related to human response. The equipment should be capable of measuring both vertical and horizontal motion. When reporting data, the bandwidth, phase, direction, and background vibration should be specified.

A-150 Dwe, B.; Sailler, J.; Hofer, J.
Schienenbahnen Theorie, Versuche und... (Ballastless railway

track - theory, tests and experiences with new track constructions).
(journal article) Verkehr und Technik, Publication #69 (1979) [in German].

Several articles are contained in this publication including: "Replacement of ballasted track on transverse sleepers by other constructors"; "Successful reduction of body-borne sound in the Vienna metro"; "Ballastless track in tunnel"; and "Modern track on solid slab in the world - a concluding review."

Most of the experience discussed in these articles indicates generally improved levels of noise and vibration with ballastless track. Based principally on the last article, there are three main groups of tracks:

1. Tracks with "double indirect" rail fastenings, with intermediate plate resting on elastic pad or shoe which rests on base on main plate and that on concrete; the rail is separated from the intermediate plate by a thin rubber pad.

2. Tracks of the Sonneville (STEDEF) type: sleepers (or connected blocks) laid on rubber on concrete. This construction "simulates" ballasted track and is particularly effective in suppressing body-borne sound. Prefabrication helps installation.

3. Many tracks with simple direct fastening systems with one rubber layer which is either under the rail or under the plate. Experience of Toronto, Hamburg, San Francisco (BART), and San Paulo shows satisfactory results when considering economic factors and environmental protection.

A-151 Hannelius, L.
Ground Vibrations Caused by Railways - Their Influence on Buildings and People.
(academic report) Reprints and Preliminary Reports, #56 Swedish Geotechnical Institute (1974) [in Swedish].

This report presents the frequency of vibrations recorded in three houses situated close to railway lines. Distances and soil conditions varied. Measurements were made on different levels in the houses. Corresponding subjective estimates of the degree of nuisance were given and compared to Dieckmanns K-Value diagram. The result shows that the combination of cohesive soils and frequencies up to 10 Hz gives the most disturbing effects. The horizontal motions of the top floors were quite considerable due to resonance. A Finnish research project is also described which investigated what effect the size of the cross section area of the fill and the depth to firm layers have on the amplitude of the vibrations caused by passing trains.

A-152 Belzer, H.W.
Zur Beurteilung Zeitlich... (Evaluation of varying vibration effect by means of an equivalent continuous value -EVC).
(journal article) VDI Berichte, no. 284, pp19-22 (1977) [in German].

Any ECV must take into account the following: 0.8 to 2 seconds are needed before a person responds to vibration; a person does not notice a single oscillation but, at least in the relevant range above 1 Hz, he has a feeling which can be described as "perception of vibration"; breaks produce recovery; for small and medium vibration effects, in case of constant vibrations, there is habituation but not for intermittent and stochastic vibrations; and tolerance of vibration effects depends very much on the background conditions and on anticipation. The above requirements are discussed in some detail including a proposed criteria and a formula.

A-153 Anonymous
Report on Vibration Records at Leytonstone House Hospital. (report) London Transport, February 24, 1955 (1955).

Vibration measurements were made with the Cambridge Universal Vibrograph at the Leytonstone House Hospital in order to determine if subway train vibrations inside a building can be determined at over 250 feet from the source and, if measurable, the magnitude of the vibration. The Hospital consists of a central three-story brick building surrounded by a number of subsidiary buildings, also of brick. Vibration records were taken on the polished oak strips of the 50' x 20' gymnasium floor (ground floor), and on the floor (soft wood boards covered with linoleum) of a first floor, 10 foot square room. The passage of trains and their directions were clearly discernible in the gymnasium. In the 10 foot square room, the trains were not audible.

These records show that whereas a maximum vertical displacement of 0.14 and a maximum horizontal movement of 0.08 thousandth of an inch were recorded on the floor of a building 60 feet away from a subway with 32-feet cover, no movement could be measured with the Universal Vibrograph at a distance of 260 feet from the same subway.

A-154 Volberg, G.
Vorschlage...U-Bahn Verkehr. (Suggestions for evaluation of noise emissions caused by underground railways).
(journal article) VDI-Berichte, no.284, 33-35 (1977)
[in German].

In this report, it is suggested that the frequency range of interest is 20-100 Hz. In accordance with definition of Guide VDI 2057 and Standard DIN 4150, it is recommended that the upper limit in inhabited rooms should be K=0.05 within 20-100 Hz which comprises of almost all frequencies produced by the underground trains. In this frequency range, there is also secondary airborne noise radiated from floors and walls. In rooms with an average absorption, the maximum level of this secondary noise should not exceed 45 dBA. This level corresponds to the minimum requirements of Guide VDI 2719. Vibration velocity should not exceed 60 dB re 5 x 10^{-8} m/sec.

A-155 Devaux, A.
Reduction of noise and vibrations which affect buildings structures caused by the passage of railway rolling stock.
(journal article) Bull Int Rail Cong Assoc, 46:12, 717/1-760/44 (1969).

Although the information contained in this report is somewhat out of date, the noise reduction procedures and results are of some interest.

Materials cut out of rubber and placed between the rail head and the ballast have resulted in a considerable reduction in every case where they have been used whether it be by the S.N.C.F. or the R.E.R. (Express Regional System) or by foreign railway administrations. This rubber layer, which is 27 mm thick, laid evenly under the track ballast results in: a gain of 14 dBA in the sound level in the areas under the concrete foundations over which trains pass; a reduction from 10 to 1 of the vibrations inflicted on the concrete foundations itself; a reduction of 3 to 4 dB in the sound level next to the track itself; and a variable reduction in sound levels in areas above the track - this sound reduction being as much as 16 dB.

A-156 Stuhler, W.
Ubersicht... (Review of procedures for measurement and analysis of mechanical vibrations in connection with...and on people in buildings).
(journal article) VDI-Berichte, no.284,pp5-11 (1977) [in German].

This paper gives criteria for the vibrational effect on people in buildings.

The provisional standard DIN 4150 Part 2, September 1975, prescribes KB limit, a "limit" (e.g., KB=0.05) being defined in terms of vibration acceleration for 1 to 2 Hz and in terms of vibration velocity for frequencies above 8 Hz with a connecting line in between 2 and 8 Hz. Two alternative ways of establishing a KB value are given which may produce entirely different results and another difficulty is that for an unambiguous determination of a periodic signal, both amplitude and phase spectra must be known and similarly, for a stochastic signal, both the power spectral density and the probability density must be known.

Guide VDI 2057, Sheets 1 and 2 (draft), February 1975, prescribes that the RMS value of a vibration signal be used to evaluate KB values. This means that individual peaks are not a basis for evaluation. It is suggested that the power spectral density also be included.

For determining the vibrational effects on buildings, a single value of the maximum vibration may be sufficient to determine the effects. However, what is needed is amplitude probability density and power spectral density. The advantage of the additional information is that judgments would be possible on distribution of single peaks, how near to resonance is the vibration, etc.

Test apparatus and procedures for determining the effects on both buildings and people in buildings are given. Also stated is what information should be included in a report evaluating these vibrational effects.

A-157 Anonymous
Preliminary Unpublished Investigations by International Union of Railways.
(report) Office for Research and Experiments (ORE), Utrecht, The Netherlands (1979).

Question D151: Influence of vibrations transmitted through the ground. This is a new question (1979) of ORE. The work will include tests of noise and vibration near railway tracks in West Germany. The final report is expected in about three years time.

Among the ORE Questions and reports which may be related to this question are:

- Question D71:
  Stresses in the rails, the ballast and in the formation, resulting from traffic loads, 13 reports.

- Question D87:
  Unconventional tracks, 18 reports.

- Question D87/Report 3
  Includes tests on static and dynamic stiffness and damping of fastenings.

- D87/RP17, April 1977:
  Resume report on unconventional tracks. This report covers types, design, construction, rail fastenings, and experience, advantages and disadvantages of slab track, and costs of nonconventional track compared with ballasted track. Conclusions include the fact that non-conventional tracks have proven themselves fully when installed in tunnels as regards minimum maintenance, minimum construction depth, maximum retention of track geometry and maximum lateral resistance. Such tracks cannot yet be recommended for use in the open because several problems have to be overcome.

- D87/RP18, October 1979:
  Enquiry report - present state of knowledge and future use. This report predicts that in the future, the slab track will be used in tunnels, to a much lesser extent on elevated structures and with virtually no installation in the open on soil formations. Most applications will be by Metro authorities and therefore, this D87 Committee will do no more work on the subject.

- Question D23:
  Determination of dynamic forces on bridges, 17 reports.

- Question D101:
  Braking and acceleration forces on bridges, about 20

reports. These forces act on abutments causing vibration although this is not considered in the reports.

- Question D60:
  Use of rubber for bridge bearings, 3 reports. Appendix 2 gives procedure for determining dimensions of rubber bearings without calculations of natural frequency.

- Question B65:
  Examination of structures by means of fatigue tests and vibration tests at resonance, Report of enquiry (1 report only), October 1963. Part 1, Survey on Fatigue, includes types of service strains, classifications of fatigue testing machines and influence of various factors on fatigue. Part 2 gives examples of machines for testing specimens and for testing real components. The report is more applicable to rolling stock than to track.

- Question C116:
  Interaction between vehicles and track, 8 reports. C116 RP1 explains power spectral density of track irregularities which should be known before and after tests of antivibration mountings and which are also useful in design of the mountings. C116 (RP4) covers the equations of motion and includes force input functions due to irregular track. This report is concerned not with track but with the motion of the vehicle, its stability, riding comfort, etc.

A-158 Bender, E.K.; Kurze, U.J.; Lee, K.S.; Ungar, E.E. Predictions of Subway-Induced Noise and Vibration in Buildings, Phase 1.

(report) Bolt, Beranek & Newman, Inc., Cambridge, MA, BBN-1823. for: Washington Metropolitan Area Transit Authority (1969).

This study predicts the vibrations and noise produced by the planned Washington Metropolitan Area Transit Authority subway in ten specific buildings near the Phase I track and compares them to acceptability criteria. Vibration isolation recommendations are made for tunnels and building substructures.

It is concluded that the vibrations will generally be below the threshold of feeling, but the associated noise is likely to be annoying, unless the WMATA cars and trackwork are so constructed that they cause considerably less ground (and tunnel) vibrations than those typical of the Toronto Transit Commission.

Criteria and general techniques for analyzing vibration transmission and the attendant noise in buildings are presented in the appendix. The prediction techniques account for effects of geometric spreading loss and dissipation of vibration in soil, building coupling loss for buildings on piles, floor-to-floor attenuation in buildings, and room absorption.

The cases of buildings with piles located at various distances from the subway structure are discussed with the aid of simplified analytical models. Vibration propagation through rock and amplification at rock-soil interfaces are treated, including the effect of rock or soil impedance on subway structure vibration.

A-159 Samavedam, G.; Cross, P.
Review of Vibration-Isolating Tracks for Tunnels.
(technical note) British Railways Board, Research and Development Division, Railway Technical Centre, Derby, England, #TN-TS-37; file 261-202-37 (1980).

This work presents a review of floating slab vibration isolation for tunnels installed in England, Japan, North America, and Germany. Fundamental principles of generation and transmission of vibrations in soils surrounding tunnels and the effect of these vibrations on people and building structures are discussed. It is concluded that the troublesome frequencies of groundborne vibrations are generally in the medium frequency range of about 30 to 250 Hz in direct fastening systems. The troublesome vibrations can be greatly reduced by floating slab trackbeds.

Vibration isolation efficiencies of existing floating tracks are discussed in the light of published practical data. It is pointed out that there are deficiencies in many of the existing designs. Appropriate dynamic analyses of floating slab tracks and vibration attenuation in soils surrounding tunnels are apparently lacking in the literature. Such studies will be presented in a subsequent work to provide a rational basis for design of floating slab tracks.

Of particular interest is the belief by the authors that long or continuous floating slabs provide better vibration isolation than discontinuous floating slabs due to dispersion of vibration energy along the length of the slab. The "Cologne Egg" rail fastener is discussed.

A-160 Alden, D.L.
YSNE Noise and Vibration Investigation Program - Subway Car Vibration Shake Test Program.

(academic report) University of Toronto, Dept. of Mechanical Engineering. for: Toronto Transit Commission (1975).

This report presents an analytical and experimental analysis of truck vibration modes. The experimental measurements incorporated an electromagnetic shaker and continuous ultraviolet recording of vibration data at a number of points on the truck. The truck and vehicle were suspended on springs with about 4.5 inch static deflection, allowing free vibration of the wheel set and truck. Resonant vibration modes were found at a number of frequencies in the range of 30 to 100 Hz. First and second bending modes are identified at 57 and 179 Hz. No measurements were made with the truck resting directly on rails or otherwise supported.

The analytical approach incorporated finite element analysis. Rigid body vertical translational and rotational axle modes were identified at 6 Hz and 8.8 Hz, respectively. The first and second axle bending modes were predicted at 59.3 Hz and 177 Hz, including gearbox and wheel. The model was subsequently applied to the case of the wheels pinned at the hubs to approximate the effect of nonfree support. Rotary inertia of the wheel was still included. The first and second axle bending mode frequencies were thus predicted to be 119 and 459 Hz, respectively. These results indicate that rail impedance may be a significant factor when measuring truck vibration modes.

A-161 Saurenman, H.J.
Groundborne Noise and Vibration Study - Toronto Transit Commission Yonge Subway Northern Extension.
(conference paper) presented at 92nd Meeting of the Acoustical Society of America, San Diego, CA (1976).

The vibration created by rail rapid transit trains operating in subways often creates ground vibration that is perceived in adjacent buildings as a low-frequency rumbling noise. With modern transit systems, it is only in rare instances that the vibration is also perceptible as mechanical motion of the building. Normally, the rumbling noise during passage of a transit train will not be audible more than 100 to 200 feet from the subway.

Early operations in the Toronto Transit Commission (TTC) Yonge Subway Northern Extension (YSNE) tunnels resulted in in-house noise due to groundborne vibration at unusually large distances from the subway. Noise due to transit train operations was clearly audible in buildings up to 800 feet from the subway structure. Because of this experience, the TTC initiated an extensive study and measurement program to determine the factors contributing to the apparently high levels of groundborne vibration and noise and, more specifically, to evaluate the potential of various procedures to reduce the noise levels experienced in buildings near the YSNE subway structures. This paper presents some of the results and conclusions of the noise and vibration part of the study. A more comprehensive summary of the study is contained in the Toronto Transit Commission Report "Yonge Subway Northern Extension; Summary, Conclusions and Recommendations," RD 115/1, (1976). Listed below is a brief summary of the points discussed in this paper.

- Groundborne vibration and noise have very narrow frequency band characteristics indicating that the transmission path from subways to buildings has a filter-like characteristic with maximum transmission at a frequency dependent on geological characteristics. The maximum transmission is at about 50 Hz in Toronto.

- Vertical vibrations of the ground surface or invert are adequate for evaluating noise produced in buildings.

- Further study is needed to determine what soil parameters have the most effect on the transmission of groundborne vibration.

- The in-building noise level can be expected to drop only 4 dBA due to a 50% reduction of train speed.

- Increasing resilience of rail fasteners is an effective method of reducing ground vibration.

- Use of resilient wheels significantly reduces the levels of ground vibration.

A-162 Wilson, G.P.
Preliminary Report on Floatation Slab Evaluation.
(preliminary report) Wilson, Ihrig & Associates, Inc., Oakland, CA.
for: De Leuw, Cather Company, Washington, DC (1975)
[proprietary information].

Preliminary floating slab tests were performed on October 1 and October 2, 1975. Numerous octave band and 1/3 octave band spectra are presented for the vibration of floating slab configurations and of noise levels in the subway. Both double-crossover and tangent line track alignments are included. Recommended modifications to the one double-crossover floating slabs design and to control transverse bending modes, was cutting the slab lengthwise between the tracks.

A-163 Dym, C.L.
Attenuation of ground vibration.
(journal article) Sound and Vibr, 10:4,32-34 (1976).

In a discussion roughly similar to that given in Reference A-59, the author describes attenuation of ground vibration as a function on distance from the source. Consideration is given to both frequency dependent and frequency independent absorption coefficients.

A-164 Derham, C.J.; Wootton, L.R.; Learoyd, S.B.B.
Vibration isolation and earthquake protection of buildings by natural rubber mountings.
(journal article) NR Technology, 6:2,21-33 (1975).

Practical design considerations in the use of natural rubber for vibration isolation of buildings are discussed, including choice of spring, damping, creep, ozone attack, and performance.

A-165 Hasselman, T.K.; Bronowicki, A.; Hart, G.C.
Dynalist II-A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems.
(final report) J.H. Wiggins Company. for: U.S. DOT; Federal Railroad Administration, FRA-OR&D-75-22-I.
avail: U.S. National Technical Information Service, PB-256-046 (1975).

A methodology and a computer program, DYNALIST II, have been developed for computing the response of rail vehicle systems to sinusoidal or stationary random rail irregularities. The computer program represents an extension of the earlier DYNALIST program. A modal synthesis procedure is used which permits the modeling of subsystems or components by partial modal representation using complex eigenvectors. Complex eigenvectors represent the amplitude and phase characteristics of rail vehicle systems which occur as a result of wheel/rail interaction, heavy damping in the suspension system, and rotating machinery. Both vertical and lateral motion are handled by the program which allows up to 25 component and fifty-degrees-of-freedom system.

A-166 Bronowicki, A.; Hasselman, T.K.
Dynalyst II, A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems, Vol 2: User's Manual.
(final report) J.H. Wiggins Company, Redondo Beach, CA., DOT-TSC-FRA-74-14.2 for: U.S. DOT; Federal Railroad Administration. FRA-OR&D-75-22.2 avail: U.S. National Technical Information Service, PB-257-733 (1975).

This is the Users Manual for the DYNALIST Program described in Ref A-165.

A-167 Bronowicki, A.; Hassleman, T.K.
Dynalist II-A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems. Vol. III: Technical Report Addendum.
(final report) J.H. Wiggins Company. for: U.S. DOT; Federal Railroad Administration, FRA-OR&D-75-22-III. avail: U.S. National Technical Information Service, PB-258-193 (1976).

Several new capabilities have been added to the DYNALIST II computer program. These include: (1) a component matrix generator that operates as a 3-D finite element modeling program where elements consist of rigid bodies, flexural bodies, wheelsets, suspension elements, and point masses assembled on a nodal skeleton; (2) a periodic and transient time-history response capability; (3) a component update capability for parametric studies; (4) an orthogonality check on component and system complex eigenvectors; (5) an option for improving low-frequency convergence under modal truncation; (7) automatic phaselag generation; (8) user-controlled scaling options on all response plots; and (9) a number of additional minor improvements. A Technical Report Addendum and a completely revised User's Manual document these changes to the previous version of DYNALIST II.

A-168 Bronowicki, A.: Hasselman, T.K.
Dynalyst II, A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems.
(final report) J.H. Wiggins Company. for: U.S. DOT; Federal Railroad Administration, FRA-OR&D-75-22-IV. avail: U.S. National Technical Information Service, PB-258-194 (1976).

Revised User's Manual for DYNALIST computer program. See Ref A-167.

A-169 Perlman, A.B.; DiMasi, F.P.
Frequency Domain Computer Programs for Prediction and Analysis of Rail Vehicle Dynamics; Vol 1: Technical Report.
(final report) U.S. DOT; Transportation Systems Center, Cambridge, MA, DOT-TSC-FRA-75-16.1. for: U.S. DOT; Federal Railroad Administration, FRA-OR&D-76-135.1. avail: U.S. National Technical Information Service, PB-259-287 (1975).

Frequency domain programs developed or acquired by TSC for the analysis of rail vehicle dynamics are described in two volumes.

Volume I defines the general analytical capabilities required for computer programs applicable to single rail vehicles and presents a detailed description of frequency domain programs developed at TSC in terms of analytical capabilities, model description, equations of motion, solution procedure, input/output parameters, and program control logic. Descriptions of programs FULL, FLEX, LATERAL, and HALF are presented. TSC programs for assessing lateral dynamic stability of single rail vehicles are also described.

A-170 Perlman, A.B.; DiMasi, F.P.
Frequency Domain Computer Programs for Prediction and Analysis of Rail Vehicle Dynamics; Vol 2: Appendices. (final report) U.S. DOT; Transportation Systems Center, DOT-TSC-FRA-75-16.2 for: U.S. DOT; Federal Railroad Administration, FRA-OR&D-76-135.2. avail: U.S. National Technical Information Service, PB-259-288 (1975).

Frequency domain computer programs developed or acquired by TSC for the analysis of rail vehicle dynamics are described in two volumes. Volume I is Reference A-169.

Volume II contains program listings including subroutines for the four TSC frequency domain programs described in Volume I.

A-171 Wright, A.T.
BART Truck Shock Loading Test,
(report) Wilson, Ihrig & Associates, Oakland, CA. for: Parsons-Brinckerhoff-Tudor-Bechtel, San Francisco, CA (1974).

The measurements were undertaken for the purpose of documenting the shock and vibration environment experienced by accessories and components mounted on the frame of trucks of the first series of BART cars under normal car-operating conditions. Magnitudes were found to exceed 30 g with half sine duration of roughly 5 ms, corresponding to a 100 Hz resonance condition.

A-172 Parson Brinckerhoff-Tudor, Bechtel
San Francisco Bay Area Rapid Transit District Demonstrations Project-Technical Report Number 8-Acoustic Studies.
(final report) Parsons Brinckerhoff-Tudor, Bechtel. for: San Francisco Bay Area Rapid Transit District (1968).

This extensive report summarizes results of measurements performed by Wilson, Ihrig, and Associates and by Stanford Research Institute, investigating noise and vibration control concepts for the Bay Area Rapid Transit District. Tests performed at the Diablo Test Track included evaluation of car equipment, rail fasteners, aerial structure noise and vibration, sound barriers, wheel damping, car interior noise, and ground vibration. Measurement locations, instrumentation, and procedures are detailed.

A-173 Wilson, G.P.
Subway Platform Vibration Levels.
(letter report) Wilson, Ihrig & Associates, Inc. for: Parsons Brinckerhoff-Tudor-Bechtel (1972) [proprietary information].

Subway station platform vibration levels are reduced from 5 to 15 dB (8 to 1000 Hz) by rail grinding. The rails were newly placed, with mill scale and other manufacturing irregularities present.

A-174 Wilson, G.P.
Primary Stiffness Resonance.
(letter report) Wilson, Ihrig & Associates, Inc. for: Parsons Brinckerhoff-Tudor-Bechtel (1978) [proprietary information].

A primary stiffness resonance in the neighborhood of 20 Hz in the WMATA system is indicated to be the cause of high levels of low-frequency groundborne vibration.

A-175 Carlson, N.; Keevil, W.R. (eds).
Chicago's Rapid Transit, Vol II: Rolling Stock/1947-1976.
(report) Central Electric Railfans Association, Bulletin 115 (1976).

This report describes the various trucks in use on the CTA transit system including the Wegman truck used on the CTA 2400 series vehicles.

A-176 Donlop Polymer, Engineering Division.
Patent Application for "Metalastic" Fastener.
(proposal) Donlop Polymer, Engineering Division., report #A364 (1980).

A patent application for the "Metalastic" fastener.

A-177 Lawrence, S.T.
TTC-LRT Trackbed studies, groundborne vibration testing, measurement and evaluation program.
(conference paper) presented at APTA Rapid Tranist Conference, San Francisco, CA (1980).

In order to evaluate changes in trackbed and trackwork design for selection of the trackbed to be installed on the SLRT route, areas of the surface section on the Toronto Subway System were used in this testing, measurement, and evaluation program.

Evaluation of the trackbed design was conducted in three phases. Phase 1 was to evaluate modifications to the track fastener assembly; phase 2 was the evaluation of ballast and tie mats; and phase 3 was the underground barrier wall study.

Generally at most test locations, vibration measurements were taken at 0, 40, and 80 feet from the center line of the test track. For most tests, a 4-car H type subway train was used as the vibration source. The test train operated at speeds of 20, 35, and 45 mph.

Only one measurement location and one train speed is presented in this report. Final interpretation of the test results has yet to be undertaken but will form part of the final reports.

A-178 Reiher, H.; Meister, F.H.
Die empfindlichkeit der Menschen gegen Ershutterungen.
(journal article) Forschungs Gebiete Ingenieurwesen, 2:11,381-386 [in German] (1931)

A-179 Dieckmann, D.
Study of the influence of vibration on man.
(journal article) Ergonomics, 1:4,347-355 (1958)

A-180 Miwa, T.
Evaluation methods for vibration effects, Part 1: Measurement of Threshold Contours of Whole-Body for Vertical and Horizontal Vibrations.
(journal article) Indust Health 5,183-205 (1967)

A-181 International Standards Organization.
Guide to the Evaluation of Human Exposure to Whole-Body Vibration [ISO-2361-1978(E)].
(approved standard) International Organization for

Standardization, Switzerland, ISO-2361-1978(E) (1978)

A-182 American National Standards Institute.
Guide to the Evaluation of Human Exposure to Vibration in Buildings.
(draft amer standard) American National Standards Institute, New York, NY, ANSI-S3.29-198X (1981)

A-183 Dym, C.L.; Gutowski, T.G.
Interstate 3A System for Baltimore City; Assessment of Traffic-Induced Ground Vibration.
(report) Bolt, Bernaek & Newman, Inc., Cambridge, MA, BBN-3076 (1975)

A-184 German Standards Institute.
DIN 4025.
(standard) (1958)

A-185 German Standards Institute.
Vibrations in Building Construction; Draft Revision.
(standard draft revision) German Standards Insititute, DIN-4150; BSI transl 71/3276 (1971)

A-186 German Standards Institute.
Vibrations in Buildings, Part 2: Influence on Persons in Buildings.
(intl standard) German Standards Institute, DIN-4150:Part 2 (1975)

A-187 British Standards Institution.
Development Guide to the Evaluation of Human Exposure to Whole-Body Vibration; Draft.
(standards discussion) British Standards Institution, BSI-DD-32 (1974)

A-188 American National Standards Institute.
Guide for the Evaluation of Human Exposure to Whole-Body Vibration.
(standard) American National Standards Institute, New York, NY, ANSI-S3.18-1979 (1979)

A-189 International Standards Organization.
Guide for the Evaluation of Human Exposure to Whole-Body Vibration, Amendment 1.
(standard amendment) International Organization for Standardization, Switzerland, ISO-2631;DAMI-1980 (1980)

A-190 International Standards Organization.
Guide for the Evaluation of Human Exposure to Vibration and Shock in Buildings; Addendum 1: Acceptable Magnitudes of Vibration.
(standard addendum) International Organization for Standardization, Switzerland, ISO-2631:DAD1-1980 (1980)

A-191 International Standards Organization.
Guide for the Evaluation of Human Exposure to Whole-Body Vibration; Addendum 2: Evaluation of Exposure to Z-Axis Vertical Vibr at 0.1 - 1.0 HZ.
(standard addendum) International Organization for Standardization, Switzerland, ISO-2631:DAD2-1980 (1980)

A-192 McKay, J.R.
Human Response to Vibration: Some Studies of Perception and Startle.
(PhD thesis) University of Southampton, Southampton, United Kingdom (1972)

A-193 Griffin, M.J.
Human Response to Vibration.
(academic course notes) University of Southampton, Southampton, United Kingdom (1980)

A-194 Wilson, Ihrig & Associates.
Unpublished internal data.

A-195 Greater London Council.
Guidelines for Environmental Noise and Vibration.
(report) Greater London Council, London, England, Bulletin #96: 2nd series (1976)

A-196 Parisian Transport Board.
Provisional Test Code for the Measurement of Vibrations in Metropolitan Railway Vehicles.
(report) Parisian Transport Board, Paris, France, TT-73-6326 (1974)

A-197 American Public Transit Association.
Guidelines for the Design of Rapid Transit Facilities.
(report) American Public Transit Association (1979)

A-198 Nichols, H.R.; Johnson, C.F.; Duvall, W.I.
Blasting vibrations and their effect on structures.
(journal article) Bureau of Mines Bulletin, #656 (1971)

A-199 Wiss, J.F.
Damage effects of pile-driving operations.
(journal article) Highway Research Record, #155 (1967)

A-200 Whiffin, A.C.; Leonard, D.R.
Survey of Traffic-Induced Vibrations.
(report) Transport and Road Research Laboratory, Crowthorne, Berks, England, LR-418 (1971)

A-201 Cauthen, L.J.
Effects of seismic waves on structures and other facilities.
(conference paper) presented at: Thord Plowshare Symposium, Davis, CA (1964)

A-202 Thoenen, J.R.; Windes, S.L.
Seismic Effects of Quarry Blasting.
(journal article) Bureau of Mines Bulletin, #442 (1942)

A-203 Gutowski, T.G.; Wittig, L.E.; Dym, C.L.
Assessment of Groundborne Vibration from Construction and Traffic for I-83 in Baltimore City.
(report) Bolt, Beranek & Newman, Inc., Cambridge, MA, BBN-3466 (1977)

A-204 Paolillo, A.
Suitability of existing vibration criteria for rapid transit systems.
(conference paper) presented at: Annual meeting of the Acoustical Society of America, Atlanta, GA (1980)

A-205 International Standards Organization.
Structural Damage from Building Vibration.
(draft standard) International Organization for Standardization, Switzerland, ISO/TC-108/SC-2/WG3 (1974)

A-206 Ungar, E.E.; Kurzweil, L.G.
Means for the reduction of noise transmitted from subways to nearby buildings.
(journal article) Shock & Vibr Digest 12:1,2-12
(1980)

A-207 Crockett, J.T.A.
Traffic vibration damage in medieval cathedrals.
(conference paper) in: Proceedings of RILEM: Vol 1. Budapest, Hungary, (publisher unknown) (1963)

A-208 International Standards Organization.
Guide to the Evaluation of Human Exposure to Vibration and Shock in Buildings; Addendum 1: Acceptable Magnitudes of Vibration.
(intl standard draft add) International Organization for Standardization, Switzerland, ISO-2631-DAD1 (1978)

A-209 Martin, D.J.; Nelson, P.M.; Hill, R.C.
Measurement and Analysis of Traffic Induced Vibration in Buildings.
(report) Transport and Road Research Laboratory, Crowthorne, Berks, England, TRRL-Supplementary-402. avail: U.S. National Technical Information Service, PB-297-336/2GA
(1978)

A-210 Martin, D.J.
Low-Frequency Traffic Noise and Building Vibration.
(report) Transport and Road Research Laboratory, Crowthorne, Berks, England, TRRL-Supplementary-429. avail: U.S. National Technical Information Service, PB-301-037/8GA
(1978)

A-211 Wilson, S.S.; Northwood, T.D.; Webster, F.W.J.
Standards of Acceptable Railway Noise and Vibration

Applicable to New Residential Developments Adjacent to Railways.
(report) S.S. Wilson & Associates, Downsview, Ontario, #W80-208-9. for: Ontario Ministry of Housing, Toronto, Ontario, Canada (1981)

PART B: GENERAL BUILDING AND GROUNDBORNE VIBRATION

B-001 Omata, S. Morita, S.
Horizontal resonance frequencies of vibration pickup on soil surfaces.
(journal article) J Acoust Soc Amer, 66:4,965-975 (1979).

Horizontal resonance frequencies of vibration transducers placed directly on soil surfaces are determined analytically. Impedance relations are developed for coupled horizontal and rocking modes of the transducer, amplification as a function of transducer base diameter, and height of center of gravity. The resonance frequency of horizontal motion of the transducer mounted on an elastic semi-infinite medium is lower than the vertical resonance frequency. The formulas are sufficient for determining the response of the sidewalk slab to horizontal excitation and should have particular relevance to interpretation of spectra of horizontal vibration measured on a sidewalk.

B-002 Hamilton, E.L.
Vp over vs and Poisson's ratios in marine sediments and rocks.
(journal article) J Acoust Soc Amer, 66:4,1093-1101 (1979).

The ratio of compression wave velocity to shear wave velocity in various marine sediments and rocks at great pressure is discussed. The data are presented primarily for interpretation of seismic wave propagation data measured for sediments and rocks beneath the ocean floor. The data are, therefore, not directly applicable to problems in groundborne vibration from rapid transit systems, but the methods and comments do have potential application to groundborne noise and vibration.

B-003 Prange, B.(ed)
Dynamic Response and Wave Propagation in Soils.
(first edition) Institute of Soil and Rock
Mechanics. Proceedings of a Conference on Dynamical Methods
in Soil and Rock Mechanics: vol 1. A.A. Balkema, Rotterdam,
The Netherlands (1978).

This book is a collection of papers by various researchers covering various topics in the field of soil-structure interaction and wave propagation. In particular, a paper presented by Werner Rucker discusses the measurement and evaluation of random vibration from a transit structure, including finite element analysis of a double-box subway founded in earth. Other papers discuss the application of finite element analysis to various types of foundations embedded in soil. Other topics which are discussed include:

- Lumped parameter models (Woods)
- Dynamic interaction of a foundation with a viscoelastic half-space (Gaul)
- Effects of piles on dynamic response of footings and structures
- Correlation methods in soil dynamics (Roesler)
- Measurement of vibrations (Prange).

B-004 Richart, F.E.(jr); Hall, J.R.(jr)
Vibration of Soils and Foundations.
(first edition), Prentice-Hall, Inc., Englewood Cliffs, NJ
(1970).

This general text concerns the problem of vibration of soils and foundations, with a significant amount of material devoted to propagation of waves in soils and the responses of structures. The particularly significant chapters are:

- Vibration of Elementary Systems

- Wave Propagation in an Elastic, Homogeneous, Isotropic Medium
- Elastic Waves in Layered Systems
- Propagation of Waves in Saturated Media
- Behavior of Dynamically Loaded Soils
- Theories for Vibrations of Foundations on Elastic Media
- Isolation of Foundations
- Instrumentation for Laboratory and Field Measurements, and Design Procedures for Dynamically Loaded Foundations.

Chapter 8, "Isolation of Foundations," discusses the use of a bentonite-slurry filled trench for the isolation of a large building from groundborne vibration from a subway. This illustration is part of a set of examples of the use of trenches or subgrade barriers to isolate foundations from incident ground vibration. Detailed experimental data are also given for the attenuation of ground vibration with the use of underground barriers. Apparently, the use of barriers is most effective against Rayleigh surface waves. A number of conclusions are given on Page 261 concerning the design of such barriers. The book is a very good reference for general problems in groundborne vibration. The frequency range for most of the data given is in the neighborhood of 1 Hz to 20 or 30 Hz, so that groundborne noise is not well represented in the audio range.

B-005 Kamperman, G.W.; Nicholson, M.A.
Transfer Function of Quarry Blast Noise and Vibration into Typical Residential Structures.
(final report) Kamperman and Associates, Downers Grove, IL.
for: U.S. Environmental Protection Agency, EPA-550/9-77-351.
avail: U.S. National Technical Information Service, PB-288-892 (1977).

This report discusses the measurement and analysis of the relationship between residential interior and exterior noise and vibration. The analysis is based on measurements of quarry blasting noise and vibration. The data are presented through a variety of noise and vibration descriptors. However, all spectra data are given as oscilloscope photographs of FFT analyses. No exterior-to-interior frequency responses or transfer functions are presented: the term "transfer function" is used in the report only to describe the difference between various descriptors. The frequency range of the FFT analyses is 0 to 100 Hz. The decay of ground vibration amplitude as a function of distance from the blast location is also discussed. There are no data or theory given concerning viscous damping or vibration energy absorption within the soil.

A number of comments in the report are particularly relevant to problems of groundborne vibration from transit systems. Evidently, none of the exterior ground vibration measurements correlated well with the interior noise level produced by the blasts, probably because of airborne blast noise. However, the authors found a close correlation between exterior ground vibration and interior C-weighted and overall noise, with standard deviations on the order of 2 to 3 dB. An empirical relationship for groundborne vibration propagation over relatively large distances such as 1000 m, is given as:

$$L(v) = 20 \log (H) + 20 B \log (D)$$

where $L(v)$ is the vibration velocity level in dB, D is the distance from the blast, and H and B are constants characteristic of the ground. The six quarries where Kamperman measured ground vibration attenuation were divided into three major groups which exhibited similar vibration propagation characteristics within each group. For quarries within a few miles of each other, vibration propagation is roughly similar. However, for widely separated quarries, vibration propagation characteristics may be quite different. A figure is included illustrating the ground vibration attenuation with distance in terms of distance normalized to charge per delay. These propagation characteristics for vibration velocity are important, because the spectral range of blast vibration is very similar to vibration from transit systems.

B-006 Beltzer, A.I.
The influence of porosity on vibrations of elastic solids. (journal article) J Sound Vibr, 63:4,491-498 (1979).

This paper discusses the effect of porosity on the propagation of elastic waves in elastic solids. Specifically, the wave-scattering caused by nonhomogeneous inclusions in a solid leads to damping of wave motion in a random mixture of elastic materials. This phenomenon is particularly observed in randomly porous material. A general dissipative model is provided for evaluating the influence of small, randomly distributed pores on the dynamic response of elastic structures. Numerical results are given for transverse wave propagation and for vibrations of a beam. The model shows that analysis of vibrations of elastic solids containing random porosity can be carried out with viscoelastic methods and that the damping of vibration caused by porosity is proportional to the fourth power of frequency. A general viscoelastic model is presented for prediction of the effects of porosity. A number of references are cited concerning the attenuation caused by the scattering of one-dimensional waves. The scattering effect is evidently insignificant unless the wavelength is similar to the radius of the scatterers. However, the discussion does concern the long wavelength limit and the modal vibrations of composite beams, e.g., concrete beams, referring to the importance of this damping mechanism for vibration isolation techniques at high frequencies. The theory might conceivably be applied to wave propagation in solids, although such application was not discussed.

B-007 New, B.M.
Effects of Ground Vibration During Bentonite Shield Tunneling at Warrington.
(laboratory report) Transport and Road Research Laboratory, TRRL 860. avail: Department of the Environment, Crowthorne, Berks, England. (1978).

This report primarily concerns the settling of buildings and compaction of soils in the neighborhood of tunnel excavation. Some reference is made to groundborne noise in buildings, but no detailed data are presented. However, some constant bandwidth frequency analyses of ground vibration within bore-holes at various distances from the excavation cutter are given, for distances up to about 20 m from the cutter face. Peaks in the vibration velocity spectra occur at about 150 Hz within a few meters of the source. At larger distances, the frequency of the spectral peak is reduced by about 50 percent. Measurement instrumentation is discussed. Arrays of three mutually perpendicular geophones were buried in bore-holes at various depths below the ground surface. The average attenuation vs. distance is evidently obtained from the geophone measurements.

B-008 Barkan, D.D.
Dynamics of Bases and Foundations. (translated by L. Drashenska)
(first edition) McGraw-Hill Book Company, Inc., New York, NY (1962).

This book is one of the basic references in the field of vibration of foundations and soils and is widely quoted in the literature on groundborne vibration from transit systems. It treats the elastic and vibratory behavior of soil bases, the theory and practice of the design of foundations under machines with dynamic loads, wave propagation from industrial sources, and problems caused by the effect of these waves on structures. Much experimental data are presented, including the ground vibration reduction achieved with trenching and sheetpiling, otherwise known as "screening," and the effect of damping in the soil.

B-009 Beltzer, A.I.
The influence of random porosity on elastic wave propagation.
(journal article) J Sound Vibr, 58:2,251-256 (1978).

A stochastic model of porosity is presented which includes size, number, and configuration of the pores as random parameters. In particular, the porosity may be described by the Poisson stochastic process. The propagation of a plane longitudinal elastic wave is treated under the condition that the pore concentration is small. The dispersion relation and the attenuation expression are averaged for an ensemble of specimens. But, because of the ergodic hypothesis, the results are true as space-averages for large objects. It is shown that in a low-frequency regime, the randomness of porosity leads to an increase in the attenuation and dispersion of the elastic wave and the corresponding explicity expressions are given. This paper is a predecessor of a paper by the same author (Ref. B-6). The treatment presented in both papers may be relevant to the absorption of vibration within porous soils during propagation, or perhaps within soils containing a random distribution of solid objects, such as river rock or gravel. A number of references are cited concerning this type of propagation problem.

B-010 Melke, J.
Ausbreitung Technisch Erregter Erschutterungen...(Spread of technically induced vibrations... prediction for protection against emission).

(journal article) VDI-Berichte, no.284,pp89-96 (1977) [in German].

This is a systematic checklist type of paper enumerating sources of vibrations, types of sources, and corresponding reductions due to geometric spread and material damping of various soils. The following factors are relevant for propagation: geological structure, soil constants such as elastic constants, pressure, porosity, and water contents. Typical factors which affect emission are given as well as a suggested formula for propagation.

B-011 Nelson, I.; Baron, M.L.; Sandler, I.
Mathematical models for geological materials for wave propagation studies.
(paper in monograph) in: Shock Waves and the Mechanical Properties of Solids. J.J. Burke (ed).
Syracuse University Press, Syracuse, NY (1971).

Four mathematical models are presented in Chapter 13 for soils and rocks and represent the state-of-the-art (in 1971)

1. An ideal elastic plastic material model with different elastic constraints in loading and unloading.

2. A variable modulus model with different constraints in loading and unloading but no specified yield condition.

3. A capped elastic plastic model for soil type materials in which the cap on the yield condition is made a function of the plastic volume and strain.

4. A capped elastic plastic model for rock in which the cap on the yield condition is a function of a strain parameter (strain hardening).

In each case, comparison of the analytical model and material test results are made.

B-012 Dawance, M.G.
Measurements and effects of vibrations in inhabited and industrial buildings.
(journal article) Annale de L' Institute Technique du Batiment et des Travaux Publics, no.115/116 (1957) [in French].

This article deals with instruments, natural frequencies of building/soil systems, and effects of vibration on people and on buildings. Particularly covered are the vibrations of machines on the ground surface.

B-013 New, B.M.
Ultrasonic Wave Propagation in Discontinuous Rock.
(report) Transport and Road Research Laboratory, TRRL report #720. avail: Department of the Environment, Crowthorne, Berks, England (1976).

Primarily, an experimental study utilizing ultrasonic frequencies. Ultrasonic frequencies (e.g., 54 kHz) were chosen because laboratory test specimens must be several times the wavelength to disregard boundary effects--with ultrasonic frequencies, small specimens could be used. Plane compressional (P) waves were used.

Open discontinuities (gaps) were completely effective, i.e., waves did not pass through the gap. This was not changed when the gap was filled with water. Closed discontinuities acted depending on stress. At high stress, the discontinuity acoustically does not exist. At lower stress, the acoustic coupling is uncertain.

B-014 Ellis, B.R.
A study of dynamic soil-structure interaction.
(journal article) Proc Inst Civ Eng, Part 2,pp 771-783 (1979).

The more flexible the ground support, the more interaction. A model steel tower on a concrete base was excited at various frequencies, in various planes with various forces. This was done on a rigid support (concrete laboratory floor) and on a flexible support (top soil over clay). It was found that (contrary to a common opinion) resonant frequency for any one mode of vibration is not constant. It has been stated that the effect of soil/structure interaction is always beneficial. Although the increase in damping is beneficial, but the lowering of resonant frequency can lead to problems if the vibrations reaching the structure are in low frequencies, e.g., in sea waves.

B-015 Grossmayer, R.; Rammerstorfer, F.G.; Ziegler, F.
Untersuchung des Verhaltens von Bauwerken.... (Investigation of behavior of buildings during earthquakes-model tests).
(journal article) Oesterreichische Ingenieur - Zeitschrift, 1979:1,15-22 (1979) [in German].

A model was built from Plexiglass to represent a three-story building and its foundation. Various types of "earthquakes" were injected into the model and vibration movements of foundations and other floors recorded. The article includes sections on coupling between building and foundation movement, apparatus and application of "earthquakes" (which are nonstationary), results of model tests, calculations of vibrations movements of the model, and comparison of test results with calculations. This simple setup allows an easy study of the response of the building to various types of input. The agreement between model results and calculations is good. Most references are in English.

B-016 Anonymous
International Symposium on Soil/Structure Interaction. (collected proceedings) Proceedings of Symposium at University of Roorkee, Sarita Prakashan, Meemt, India (1977).

Theme IV covers:

- "A tested soil/structure model for surface structures" (a finite element model with examples)

- "The dynamic soil/structure interaction on bridge sites" (effect of valley shapes on seismic behavior of the valleys; both horizontal and vertical seismic accelerations could be used as input to the finite element model)

- "Soil/structure interaction during blasting"

- "Foundation type and seismic response of buildings" (single, two-, five-, and ten-story buildings with different foundation flexibilities were analyzed and damage data of 1957 Mexico earthquake were qualitatively analyzed)

- "Soil/structure interaction effects in structural response to earthquake motions" (effects of flexibility of soil/foundation system on time period of vibration of some typical structures and their response to earthquake motion were analyzed)

- "Vibratory densificaton of cohesionless media."

B-017 Srinivasulu, P.; Vaidyanathan, C.V.
Handbook of Machine Foundations.

(first edition) McGraw-Hill Publishing Co, Ltd., New Delhi, India (1976).

Although this book is for stationary machines, some sections have application to groundborne vibration from transit trains. The physical properties of the elastic bases and their experimental evaluation, equipment producing vibrations, and experimental determination of soil contents are covered. Spring stiffness of elastic supports are covered for soil with vertical, horizontal rocking, and torsional motions; elastic pads, for one and N pads, with various motions; steel springs; and piles. There is also a section on the damping coefficient.

B-018 Brebbia, C.A.; Tottenham, H.; Warburton, G.B.; Wilson, J.; Wilson, R.
Vibrations of Engineering Structures.
(first edition) Computational Mechanics, Ltd., Southampton, England (1976).

A chapter is included on approximate methods of calculating natural frequencies and dynamic response of elastic systems with forumulas for multi-story buildings; a chapter on machine foundations covering rigid and flexible based, low-tuned and high-tuned foundations with design codes; a chapter on vibration of axisymmetric shells, e.g., chimneys, cooling towers; and a chapter on response of continuous elastic systems to random loads and earthquake and tall building problems with response to ground motion. Other chapters include vibration of multi-degree-of-freedom systems, eigenvalue-eigenvector solutions, Rayleigh-Ritz methods, finite element techniques, plate bending, transient response of structures, recent advances in structural vibration, and random vibrations. Many references are given.

B-019 Martin, D.J.; Nelson, P.M.; Hill, R.C.
Measurement and Analysis of Traffic-Induced Vibrations on Buildings; and Low-Frequency Traffic Noise and Building Vibration.
(report) Transport and Road Research Laboratory, Suppl reports #402 and #429. avail: Dept of the Environment, Crowthorne, Berks, England (1978).

The work on traffic vibration has continued with a study of building response to traffic vibration at four sites where a high degree of bother with vibration had either been experienced or was expected. The results were in agreement with a previous experiment where it was shown that the principal cause of building vibration was excitation of the building by low-frequency airborne sound transmitted through the windows. At all sites, floor vibrations were generated in two frequency ranges: at 63-125 Hz corresponding to the excitation frequencies of vehicle exhaust noise; and at 10-25 Hz, corresponding to the natural frequencies of particular floors. In all cases studied, it was found that the level of floor vibration was well below that which would normally give rise to minor building damage. This report includes numerous charts of vibration and noise spectra.

B-020 Gash, R.; Klippel, P.
Evaluation of dynamic stresses in building floors and other building components under action of explosive blasts and impact loads.
(journal article) Die Bautechnik, 1976:11,379-387 & 1976:2, 417-421 (1976).

Mathematical models of both steady state and transient excitation of buildings. Two hundred and eighty-eight cases of beams with useful end conditions were calculated to show the proportionality of stress to vibration velocity. Vibration displacements and accelerations were also calculated to show lack of such proportionality. The calculations include absolute and relative quantities. The transient loads used in calculations are shown, namely half sinusoidal pulse, explosion pulse, and three blast vibrations--the longest about one second duration. The results and description of blast excitation are presented in many graphs. Large stresses occur only when the fundamental natural frequency is near the main excitation frequencies. Criteria for potential damage due to various levels of transient vibration are given.

B-021 Splittberger, H.
Effects of vibrations on buildings and on occupants of buildings.
(conference paper) in: Proceedings of Symposium on Instrumentation for Ground Vibration and Earthquakes, London, pp 147-152. Institution of Civil Engineers, London, England (1978).

Vibrations caused by quarry blasting and forging hammers were measured outside a house, at the foundation, and on the first floor. Transfer functions were developed based on these measurements. Large differences were observed between the vibration measured on the floor, on a chair, and on a table (both on the same floor). For this reason, vibration should be measured on the floor at the point of greatest amplitude, which is commonly found at mid-span.

Acceptable limits to occupants according to ISO-2631, DIN 4150, and VDI 2057 are discussed. Evidence suggests that there will be complaints if vibrations are only slightly above the threshold of perception.

Probability of damage depends not only on dynamic loadings caused by vibrations and on number of cycles but also on soil, foundation, construction, and age of building. This is the reason why recommended limits vary. The problem is not yet satisfactorily solved. Some limits are also shown. A building model is developed to estimate inertia forces and shear stresses.

B-022 Redpath, B.B.
Seismic Refraction Exploration for Engineering Site Investigations.
(report) Explosive Excavation Research Laboratory, Livermore, CA, May 1973 (1973).

This report is a summary of the theory and practice of using the refraction seismograph for shallow, subsurface investigations. It is intended to be a guide to the application of the technique and not a comprehensive analysis of every aspect of the method. The report begins with the fundamentals and then progresses from time-intercept calculations to interpretations using delay times. The limitations of this exploration tool are discussed, and other applications of the equipment, such as uphole surveys, are described. The report also recommends field procedures for performing refraction surveys.

B-023 Crice, D.
Shear Waves - Techniques and Systems.
(trade report) Geometric Nimbus, Sunnyvale, CA, (date uncertain).

The measurement of shear wave velocities as a function of soil depth is discussed. Relatively broad use of pressure waves has been made due to the comparative ease with which pressure waves may be generated and detected. However, increasing interest is developing in the measurement of and use of shear wave velocity data. Shear wave velocity data are more directly related to shear strength and other engineering parameters and may be used to predict dynamic response of foundations, requiring certain major projects such as nuclear power plants. The discussion includes wave types, basic

measurement approaches, types of seismographs, sensors, energy sources, surface shear waves, cross-hole surveys, downhole surveys, refracted shear waves, and potential problems during measurement.

B-024 Clough, R.W.; Penzien, J.
Dynamics of Structures.
(first edition) McGraw-Hill Book Company, New York, NY (1975).

This is a comprehensive text regarding the dynamics of structures. A detailed discussion of single-degree-of-freedom systems, multi-degree-of-freedom systems, distributed parameter systems, random vibration, and structural response to earthquake motion, is included.

B-025 Winkler, K.; Nur, A.
Pore Fluid and Seismic Attenuation in Rocks.
(journal article) Geophys Res Letters, 6:1 (1979).

B-026 Johnston, D.H.; Toksoez, M.N.
Ultrasonic P and S wave attenuation in dry and saturated rocks under pressure.
(journal article) J Geophy Res, no.85 (1980).

B-027 Anonymous
Handbook of Physical Constants. Memoir 97.
(first edition) Geological Society of America (1966).

B-028 O'Connell, R.J.; Budiansky, B.
Viscoelastic properties of fluid saturated cracked solids.
(journal article) J Geophys Res, no.82 (1977).

B-029 Northwood, T.D.
Isolation of building structures from ground vibration.
(paper from monograph) in: Isolation of Mechanical Vibration

Impact and Noise. J.C. Snowdon; E.E. Ungar (eds), pp 87-101 American Society of Mechanical Engineers, New York, NY (1973).

Vibration isolation of a building is appropriate if vibration levels would otherwise be higher than acceptable for the proposed building use. Criteria of acceptability usually relate to subjective reactions of the occupants or, in some instances, to the vibration sensitivity of delicate instruments that will be used in the building. Typical occupancies that might be vibration-sensitive are apartments, laboratories, hospitals, theatres, and concert halls. The most common vibration problems result from road and rail traffic; indeed, the most common application of vibration isolation is for buildings built over underground rail lines. Vibration isolation for a building follows conventional methods, but it must take into account the foundation/soil interaction and must also provide adequate protection against wind-induced vibrations and possible earthquake hazard.

B-030 Wood, J.H.
Earthquake response of a steel frame building.
(journal article) Intl J Earthq Eng Struct Dyn, 4,349-377 (1976).

B-031 Chopra, A.K.; Gutierrez, J.A.
Earthquake analysis of multi-story buildings including foundation interaction.
(journal article) Intl J Earthq Eng Struct Dyn, 3,65-77 (1974).

B-032 Veletsos, H.S.
Dynamics of Structure-Foundation Systems.
(paper from monograph) in: Structural and Geotechnical Mechanics. W.J. Hall (ed), Prentice-Hall, Englewood Cliffs, NJ (1977).

B-033 Scanlan, R.H.
Seismic wave effects of soil - structure interaction.
(journal article) Intl J Earthq Eng Struct Dyn, 4,379-388 (1976).

B-034 Bycroft, G.N.
The magnification caused by partial resonance of the foundation of ground vibration detection.
(journal article) Trans Am Geophys Union, 38, 928-930 (1957).

B-035 Ewing, W.M.; Jardetzky, W.S.; Press, F.
Elastic Waves in Layered Media.
(monographic series) Lamont Geological Observatory, Contribution no.189. McGraw-Hill Book Company, Inc., New York, NY (1957).

This well-quoted text presents a general treatment of the theory of elastic wave propagation in layered media. Major subject areas include:

- Fundamental equations and solutions
- Homogeneous and isotropic halfspaces
- Two semi-infinite mediums in contact
- Layered half-space
- Effects of gravity, curvature, and viscosity
- Plates and cylinders
- Media with variable wave propagation velocity

Much of the discussion employs cylindrical coordinates to treat azimuthally symmetric problems. Of particular significance is a discussion of azimuthally symmetric wave propagation in an infinite medium with a cylindrical cavity.

B-036 Haupt, W.
Isolation of Ground Vibrations at Buildings.

(report) Building Research Summaries. Her Majesty's Stationary Office, No.6,73-79. Detailed report in German available. from: Informationsverbundzentrum Raum und Bau, Stuttgart (1979).

Haupt presents results of measurements and finite element analysis techniques to assess the attenuation of ground vibration by solid screens in sand. A strong dependence is identified between barrier insertion loss and the ratio of cross-sectional area to the square of the Rayleigh wavelength; the larger the ratio, the greater the loss. The analysis is for barriers located in the far-field. Greater loss is obtained for barriers located close to the source.

PART C: GENERAL REFERENCES

C-001 Von Gierke, H.E.
Guidelines for Preparing Environmental Impact Statements on Noise.
(report) Committee on Hearing, Bioacoustics, and Biomechanics Assembly of Behavioral and Social Sciences (CHABA), Working Group 69 National Research Council. avail: National Technical Information Service, AD-A044384 (1977).

The guidelines proposed in this report are the result of the deliberations of the CHABA Working Group 69 from 1972 to 1976. Guidelines are proposed for the uniform description and assessment of the various noise environments potentially requiring an Environmental Impact Statement for Noise. In addition to general, audible noise environments, the report covers separately high-energy impulse noise, ultrasound, infrasound, and the environmental impact of structureborne vibration. Of particular interest is the recommendation of a weighted vibration level that can be used for a single number assessment of impact from vibration. The weighted vibration level is based on the criteria curves of ISO 2631.

C-002 Ottesen, G.E.; Vigran, T.E.
Measurement of mechanical input power with an application to wall structures.
(journal article) Appl Acoust, 12:4,243-251 (1979).

A simple method is presented for measuring mechanical power input to a structure by direct analogue multiplication and integration of force and velocity signals. The influence of phase errors is controlled through measurement of both the real and the imaginary components. The method is applied to measurements on partition walls, and agreement is obtained between input power and dissipated power computed from velocity and loss factor measurements on the wall surfaces. The method is claimed to be applicable for a steady-state measurement of the loss factor and, furthermore, that the power conversion efficiency, the ratio between the radiated sound power and input power, is a relevant factor for characterizing the radiation properties of mechanically excited partition walls. Using digital techniques for measurement of mechanical input power is not mentioned.

C-003 Fidell, S.; Teffeteller, S.; Horonjeff, R.; Green, D.M. Predicting annoyance from detectability of low-level sounds. (journal article) J Acoust Soc Amer, 66:5,1427-1434 (1979).

The relationship between the predicted detectability and judged annoyance of 24 low-level sounds heard in three noise backgrounds was investigated by an adaptive paired comparison procedure under free-field listening conditions. The predicted detectability of the set of sounds accounted for almost 90% of the variance in judgments of annoyance made in the most commonplace (falling spectrum) background noise environment. Conventional methods of predicting annoyance did not yield significantly higher correlations than a detectability-based method in two other unusually shaped background noise environments. The article may have significance concerning the quantification of human response to low-level groundborne noise from subways, although noise of such character is claimed specifically by the author to be significantly less intrusive than noise of similar or less energy due to footfalls, mechanical impacts, or other noises with significantly more energy in the high-frequency range. Also, airborne noise from a train passby produced a considerably lower level of human response than was predicted by the model. The detectability of broadband signals heard in broadband noise is given as:

$$d = n \times S/N \times W^{1/2}$$

where "n" is an efficiency factor [taken as 0.4], "S/N" is the ratio of sound powers, and "W" is the 1/3 octave bandwidth centered at the signal frequency. For broadband signals and background noise, individual detectabilities are calculated for each frequency band. The detectability is then calculated from the set of detectabilities by taking the maximum value or by computing a vector sum.

C-004 Bendat, J.S.; Piersol, A.G.
Random Data: Analysis and Measurement Procedures.
(first edition) John Wiley and Sons, Inc., New York, NY (1971).

This well-known book describes the measurement and analysis of random data, including the use of numerical techniques and the Fast Fourier Transform (FFT) method. The book is of general nature and is therefore a basic reference for the development of measurement and analysis approaches. A good discussion of the measurement of cross-power spectral density using numerical techniques is included.

C-005 Cremer, L.; Heckl, M.
Structureborne Sound. Translated and revised by E.E. Ungar.
(first edition) Springer-Verlag, New York (1973).

This general reference book concerns the propagation of vibration through and the radiation of sound from structures. The chapter headings include: "Definition, Measurement, and Generation of Structureborne Sound," "Survey of Wave Types and Characteristics," "Damping," "Impedances," "Attenuation of Structureborne Sound," and "Sound Radiation from Structures." The measurement of vibration forces, accelerations and velocities, and driving point impedance is described in detail. Also discussions are included of the electrical characteristics of various transducers used for the measurement of force, pressure, acceleration, velocity, displacement, and impedance. The book is widely quoted in the literature on noise and vibration.

C-006 Harris, C.M.; Crede, C.E.; Ungar, E.E. (eds).
Shock and Vibration Handbook.
(first english edition) McGraw-Hill Book Company, New York, NY (1976).

This is a well-known handbook concerning a large variety of vibration-related topics. Both theoretical and practical aspects of vibration measurement and analysis are discussed. Topics covered include: transducers, measurement techniques, vibration theory, nonlinear vibration, random data analysis, numerical methods, vibration in structures induced by ground motion, vibration isolation, damping, and the effects of shock and vibration on man.

C-007 Brown, F.T.
Dynamics of Flexibly Supported Tunnels and other Roadbeds.
(technical report) Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, MA, DSR-76107-1. for: U.S. Department of Commerce, contract C-85-65. avail: U.S. National Technical Information Service, PB-173-645 (1966).

This report presents a theoretical analysis of flexibly supported tunnels using the model of an elastically supported Bernoulli-Euler beam with linear damping. The methods outlined by Kenney (Ref. C-10) are used. The discussion concerns a hypothetical tunnel floated hydraulically within an outer shell. Train speeds transcend the so-called critical velocity which may occur at lower speeds. For the case of no damping, the critical velocity corresponds to a train speed at which the solutions to the mathematical model blow up. The report presents no information regarding the effects of founding conditions on vibration radiation into the surrounding soil. It does not appear that the results may be useful for studying groundborne vibration from conventional transit systems.

C-008 Mathews, P.M.
Vibrations of a beam on an elastic foundation.
(journal article) Zeitschrift angewesen fur Mathematik und Mechanik (ZAMM), 38:3/4,105-115 (1958).

This paper is the first of two papers on the dynamics of an elastically supported rail subject to a moving oscillatory point load, including the effects of translation velocity, load frequency, and foundation stiffness and damping. However, a detailed analysis of the effects of damping are reserved for a later publication by the same author. Evidently, practically all of the results of this paper were presented in a dissertation by Professor B. K. Hovey [University of Gottingen, 1933] and the second paper is based on the work of Kenney (Ref. C-10).

In this present paper, the equations of motion are solved and discussed in detail for the following cases:

- A concentrated static load at the origin.
- An alternating load applied at the origin.
- A moving load of constant magnitude.
- A moving and alternating load in the absence of damping.

The case of nonzero damping is left to the second paper. The fourth case is the most interesting in that the so-called "critical velocity" (referred to in the literature as the velocity at which undamped beam displacements become infinite) is reduced to zero as the excitation frequency approaches a "critical frequency." The critical velocity and critical frequency are given by:

$$v_c = (4EIk/d^2)^{1/4}$$

$$f_c = \frac{1}{2\pi} \left(\frac{k}{d}\right)^{1/2}$$

where "d" is the density of the beam in mass units per unit length and "k" is the foundation stiffness in force units per unit deflection per unit beam length. The remaining symbols have their usual meaning. Note that the critical frequency of the system is simply that of its single-degree-of-freedom "design" resonance. The implication is that at the resonance frequency, the critical velocity is lowered. Conversely, for nonzero translation velocities less than the critical velocity, the critical frequency is reduced from its single-degree-of-freedom resonance frequency.

C-009 Mathews, P.M.
Vibration of a beam on elastic foundation - II.
(journal article) Zeitschrift angewesen fur Mathematik und Mechanik (ZAMM), 39:1/2,13-19 (1959).

This paper is the second of two papers on the subject of an elastically supported beam on an elastic foundation subject to a translating oscillatory load of the form:

$$F(x,t)=F\cos(wt)\ \Delta\ (x-vt)$$

where "w" is the oscillatory frequency, "v" is the translational velocity, and "Δ" is the Dirac delta function. The variables "x" and "t" are the position and time variables, respectively. In the previous work, the effect of foundation damping was neglected in the detailed analysis. In this paper, the effect of damping is considered for an alternating load at the origin and a translating load of constant magnitude. The case of a translating oscillatory load is not considered in detail due to the complexity of the solution, requiring the determination of four complex roots to a fourth order differential equation. The remaining discussion is essentially similar to that presented by Kenney (Ref. C-10).

This paper presents a detailed solution and discussion of the problem of the steady-state deflection of an elastically supported beam under a translating concentrated static force. The case of an oscillating force is not considered, and by transformation to a reference frame moving with the force, the time dependence is completely removed. Several interesting figures are presented illustrating the relationships between wavelength and translation velocity, and deflection and moment amplification factors and translation velocity. At critical translation velocity, the undamped case includes infinite deflection and infinite wavelength. Above critical velocity, undamped finite amplitude harmonic waves are supported in both directions.

C-010 Kenney, J.T.(jr)
Steady-state vibrations of a beam on elastic foundation for moving load.
(journal article) J Appl Mech, 21:4,359-364 (1954).

This paper presents a detailed solution and discussion of the problem of the steady-state deflection of an elastically supported beam under a translating concentrated static force. The case of an oscillating force is not considered, and by transformation to a reference frame moving with the force, the time dependence is completely removed. Several interesting figures are presented illustrating the relationships between wavelength and translation velocity, and the relationships between deflection and moment amplification factors and translation velocity. At critical translation velocity, the undamped case includes infinite deflection and infinite wave-length. Above critical velocity, undamped finite amplitude harmonics waves are supported in both directions with infinite extent. The presence of viscous damping in the foundation serves to reduce amplification factors at all velocities below critical velocity, while above critical velocity, the presence of damping may increase the ratio of maximum moment under load to static moment under load. However, in this case, the amplification factor is less than unity. This paper is cited often in the literature concerning the dynamics of railroad rails. However, the most general case of a translating oscillatory force is treated by Mathews (Ref. C-8, C-4).

C-011 **Meisenholder, S.G.; Weidlinger, P.**
Dynamic interaction aspects of cable-stayed guideways for high speed ground transportation.
(journal article) Trans ASME:J Dyn Sys Meas Control, June, pp180-192 (1974).

The dynamics of a long span (200 to 600 ft) cable-stayed guideway for future high speed tracked levitated vehicles are discussed. A design approach is described in which a cable-stayed guideway structure can be synthesized to simulate the behavior of a beam on an elastic foundation. Parametric results are presented for the dynamic response of a beam on an elastic foundation. Optimum cable and tower configurations are developed for this guideway concept and a typical conceptual design is described.

C-012 **Mead, D.J.**
Free wave propagation in periodically supported, infinite beams.
(journal article) J Sound Vibr, 11:2,181-197 (1970).

The notion of propagation constants for the free harmonic motion of infinite beams on identical, equispaced supports is primarily reviewed. Expressions are then derived for the flexural propagation constants for beams on rigid supports

which exert elastic rotational restraint and also for beams on flexible supports. A beam on rigid supports has one propagation constant and a beam on flexible supports has two propagation constants for each frequency.

Detailed consideration of the propagation constant leads to the conclusion that a freely propagating harmonic flexural wave in such a beam must be regarded as a wave group, having components of different wavelength, phase velocity, and direction. The magnitudes of the components in some special cases are examined. The interaction between these groups and convected pressure fields is considered in qualitative terms. A mechanism is shown to exist whereby slow, subsonic convected pressure fields can generate flexural waves of supersonic velocity which can radiate sound.

C-013 Sharma, C.B.
Vibration characteristics of thin circular cylinders.
(journal article) J Sound Vibr, 63:4,581-592 (1979).

In this paper, a unified treatment is given to the problem of the vibration characteristics of thin circular cylindrical shells with various end conditions with the aid of the kinematic relations from Sanders first-order shell theory. A simple, variational technique is applied to give a cubic frequency equation. This cubic is reduced to two simple, linear relations for the frequency parameter, by incorporating an engineering approximation relating deflections in general and in the inertia components only. Expressions for evaluating mode shapes are also given. Results found by using the present technique are compared with some previous exact analysis results. Frequencies calculated in the case of a given cylinder are shown to agree well with some available observed results. This paper may have some relevance for detailed theoretical modelling of circular tunnels.

C-014 Lyon, R.H.
Statistical Energy Analysis of Dynamical Systems: Theory and Applications.
(first edition) MIT Press, Cambridge, MA (1975).

This book presents the basic theory and application of Statistical Energy Analysis (SEA) to estimate the response of complex dynamical systems. The book is divided into two parts: Basic Theory and Engineering Applications. Both the derivation of the basic theory and the discussion concerning parameter evaluation include numerous useful examples. The final chapter shows the application of SEA to the vibration of a re-entry vehicle. The technique of SEA may be useful for evaluating building response to groundborne vibration and perhaps for evaluating transit vehicle truck vibration at high frequencies.

C-015 Kovalenko, G.P.
Pressure pulse on the boundary of an elastic inhomogeneous half plane.
(journal article) J Appl Mech Tech Physics, January, pp832-836 (1976) [English translation of Zhurnal Priklad Part I July/August, 123-127 (1974)].

A pressure pulse of constant velocity along the boundary of an elastic inhomogeneous half plane has been examined in References 1 and 3 (listed in the present article). In Reference 3, the problem was solved using Laplace time transformation. An analogous problem is solved here for an elastic half plane with variable Lame parameters and density of the medium.

C-016 Ghosh, M.L.
On the propagation of Love's waves in an elastic layer in the presence of a vertical crack.
(journal article) Proc Vibr Problems, 15:2,147-165 (1974)

Inst of Fundamental Technical Research, Polish Academy of Sciences.

This paper concerns an elastic layer lying on a rigid half-space. It is desired to study the scattered field produced by a vertical crack at the upper surface when a horizontally polarized shear wave, propagating in the elastic layer is incident on the crack. The problem is reduced to a solution of a modified Wiener-Hopf equation. Assuming the length of crack is much shorter than the thickness of the layer, fields of transmitted and reflected waves were determined. Diffracted waves can be described by superimposition of Love waves and nonpropagating disturbances.

C-017 Wierzcholski, K.
The existence of a surface wave in a nonhomogeneous isotropic semi-infinite elastic body.
(journal article) Proc Vibr Problems, 15:14,330-335 (1974)
Inst of Fundamental Technical Research, Polish Academy of Sciences.

Starting with a time dependent stress field inside the body, an eigenvalue problem is considered for a constant shear modulus, constant density, and variable Poissons ratio. Making use of the uniform method of Frobenius indeterminate coefficient, the author arrives at a series form of a surface stress wave and the dispersion equation for the nonhomogeneity type assumed. It is proved that the dispersion equation defines at least one phase velocity in the segment [0,1] if the wavelength is bounded below by a constant depending on a nonhomogeneity parameter.

C-018 Mandal, S.B.
Diffraction of elastic waves by a rigid half plane.
(journal article) Proc Vibr Problems, 13:4,331-343 (1971).

Inst of Fundamental Technical Research, Polish Academy of Sciences.

This paper deals with an elastic wave polarized in a vertical plane. The diffraction by a half plane has been solved by a number of investigators including the use of Wiener-Hopf method which is associated with the difficulty of decomposition into certain functions. Here is an alternative approach using the transformation into parabolic coordinates which reduces the problem on the side of the plane to a simple boundary value problem.

C-019 Chalczyk, F.; Rafa, J.; Wlodarozyk, E.
Propagation of two dimensional nonstationary stress waves in a semi-infinite viscoelastic body produced by a normal load moving over the surface.
(journal article) Proc Vibr Problems, 13:3,241-257 (1971).
Inst of Fundamental Technical Research, Polish Academy of Sciences.

A linear load applied suddenly moves with a constant velocity. Closed form formulae are obtained for components of the stress field. Numerical solutions are given in graph form. Some comparisons with the case of elastic medium are given. The solution is a Green's function.

C-020 Groetenhuis, P.
A state-of-art review on trends in design for the shock and vibration environment.
(conference paper) in: Vibration Shock and Noise. Proceedings of Symposium by Society of Environmental Engineers, London, pp 85-99 (1979).

This paper is a discussion of the effects and inter-relationships of the factors resulting from an increase in power of machines. These factors resulting from higher levels of vibration include: noise, discomfort, wear, fatigue, malfunctioning, and loss in reliability. Criteria and dynamic characteristics are discussed including testing to verify if a component or system can withstand specific shock and vibration loadings.

C-021 Yih-Hsing, P.; Chao-Chow, M.
Diffraction of Elastic Waves and Dynamic Stress Concentration.
(first edition) Crane, Russak & Co., New York, NY (1973).

In Chapter III.8, the transient interaction problem of a shell and an elastic medium are reviewed with five studies of interaction of an acoustic wave and an elastic cylindrical shell and four studies of transient interaction between an elastic wave and an elastic shell. An integral equation method is given for a thin elastic cylindrical shell bound to an elastic medium subject to a unit stress incident P wave. Approximate techniques for solving transient structure/medium interaction problems are described, in particular, the method of substitute kernal and the trapezoidal approximation.

C-022 Keropyan, K.K.; Chegolin, P.M.
Electrical Analogues in Structural Engineering. J.M. Prentis (ed).
(first edition) Edward Arnold Publishers, Ltd., London, England (1967).

Electrical analogues of vibrating frameworks are presented. Topics include: free and forced vibrations of beams and frames, comparison of different methods for studying the dynamics of structures and electrical circuit theory, analogues for finite differences, determination of the natural frequencies of beams and frames, and application of the direct simulation method to the dynamics of structures.

C-023 Puro, A.E.
Solutions of the equation of elasticity theory for a nonhomogeneous medium.
(journal article) Sov Appl Mech 11:3,267-271 (1975).
[translation of Prikladnaya Mechanika]

Elasticity theory solutions for nonhomogeneous media are investigated. It is shown that there exists a relation among the equations of the plane, axisymmetric and three dimensional problems. The application of the method of separation of variables leads to a fourth-order ordinary differential equation with variable coefficients; this equation is related to the system of differential equations. A Boussinesq (static) problem is considered.

C-024 Fryba, L.
Vibration of Solids and Structures under Moving Loads.
(first edition) Noordhoff International Publ, Lieden, The Netherlands (1972).

This test covers a large number of combinations of beams and plates on elastic foundations. Both moving and stationary loads are considered. The forcing functions are harmonic, continuous, and arbitrarily varying in time.

C-025 Pekeris, C.L.; Lifson, H.
Motion of the surface of a uniform elastic half-space produced by a buried pulse.
(journal article) J Acoust Soc Amer, 29:11,1233-1238 (1957).

An exact solution is obtained for the motion of the surface of a uniform elastic half-space due to the application at a depth H below the surface of a concentrated vertical force. The time variation of the applied force is assumed to be represented by the Heaviside unit function. The unit for the horizontal and vertical components of displacement is cast in the form of single integrals over a fixed range, and these have been evaluated on the electronic computer of the Weizmann Institute (WEIZAC). The assumed source emits both S waves and P waves. Beyond a distance R from the epicenter, which is equal to $H/\sqrt{2}$ in the case $\lambda = \mu$, the original S wave is converted on reaching the surface into a diffracted SP wave travelling along the surface. At large ranges, the SP phase is more pronounced than the P phase. The S phase is marked by a finite jump for $r<R$ and by a logarithmic infinity for $r>R$. The coefficient of the logarithmic term is zero both at $r=R$ and at large ranges, having a sharp maximum at $r=1.004R$. There is no Rayleigh wave at $r<R$. At large ranges ($r/H>>1$), the solution approaches the form of the solution for the surface pulse.

C-026 Miller, G. F.; Pursey, H.
On the partition of energy between elastic waves in a semi-infinite solid.
(journal article) Proc Royal Soc London-A, 233:pp55-69 (1955).

Expressions are derived for the power radiated in the compressional, shear, and surface waves set up by a circular disk vibrating normally to the free surface of a semi-infinite isotropic solid. The total radiated power is also calculated independently by integrating the displacement velocity over the area of the source.

The theory is designed for a general type of multi-element radiator in the form of an array of elements on the circumference of a circle. The calculation of the total power here involves a "mutual admittance" function, a table of which is given for the case when the Poisson's ratio of the medium is equal to 1/4. The theory is applied to a three-element radiator, and it is shown that the efficiency of radiation in the compressional mode can be varied between wide limits by varying the distance between the elements.

Finally, an approach is suggested for problems in which the most suitable idealized boundary condition is one of known displacement under the radiator, the stress being zero elsewhere on the free surface. It is shown that the stress under the radiator satisfies an integral equation whose kernel is derived from the mutual admittance function.

Of particular interest is the partition of energy between various wavetypes at a large distance from a disc oscillating vertically on the surface is for Poisson ration 0.25:

Rayleigh Wave	67.3%
Shear Wave	25.8%
Compression Wave	6.9%

C-027 Greenfield, J.
Seismic Radiation from a point source on the surface of a cylindrical cavity.
(journal article) Geophysics, 43:6,1071-1082 (1978).

The solution could be used as the first step towards characterizing vibration radiation from subway tunnel structures. An extension of this model might include a cylindrical shell placed within the cylindrical cavity to represent a tunnel liner.

C-028 Harkrider, D.G.
Surface waves in a multi-layered elastic media I: Rayleigh and Love waves from buried sources in a multi-layered elastic half-space.
(journal article) Bull Seismol Soc Amer, 54:2,627-679 (1964).

A matrix formulation is used to derive integral expressions for the time transformed displacement fields produced by simple sources at any depth in a multilayered, elastic, isotropic, solid half-space. The integrals are evaluated for their residue contribution to obtain surface wave displacements in the frequency domain. The solutions are then generalized to include the effect of a surface liquid layer. The theory includes the effect of layering and source depth for Rayleigh waves from an explosive source, Rayleigh waves from a vertical point force, and Rayleigh and Love waves from a vertical strike slip fault model. The theory presented here lays the groundwork for later papers in which theoretical seismographs are compared with observations in both the time and frequency domain.

C-029 Biot, M.A.
Theory of propagation of elastic waves in a fluid-saturated porous solid I: low-frequency range.
(journal article) J Acoust Soc Amer, 28:2,168-178
(1956).

A theory is developed for the propagation of stress waves in a porous elastic solid containing a compressible viscous fluid. The emphasis of the present treatment is on materials where fluid and solid are of comparable densities, (e.g., water-saturated rock). The paper is restricted to the low-frequency range where the assumption of Poiseuille flow is valid. The extension to the higher frequencies is treated in Reference C-30. It is found that the material may be described by four nondimensional parameters and a characteristic frequency. There are two dilatational waves and one rotational wave. The physical interpretation of the result is clarified by primarily treating the case where the fluid is frictionless. The case of a material containing a viscous fluid is then developed and discussed numerically.

intuitively as representing outgoing waves.

C-035 Gregory, R.D.
The propagation of waves in an elastic half-space containing a cylindrical cavity.
(journal article) Proc Camb Phil Soc, 67:pp689-710 (1970).

The problem of the propagation of time harmonic waves in an isotropic elastic half-space containing a submerged cylindrical cavity is solved analytically. Linear plane strain conditions are assumed. Using an expansion theorem proved in a previous paper, the elastic potentials are expanded in a series form which automatically satisfies the governing equations, the conditions of zero stress on the flat surface, and the radiation conditions at infinity. The conditions of prescribed normal and tangential stresses on the cavity walls are shown to lead to an infinite system of equations for the expansion of coefficients. Three applications of the general theory are presented dealing respectively with the production, amplification, and reflection of Rayleigh waves.

C-036 Jette, A.N.; Parker, J.G.
Excitation of an elastic half-space by a buried line source of conical waves.
(journal article) J Sound Vibr, 67:4,523-532 (1979).

A formal solution is obtained to the problem of a buried line source of conical waves propagating at a constant phase velocity in an isotropic elastic half-space. By applying the boundary conditions at the free surface, it is determined that the reflected field, in addition to the incident field, requires addition of a scalar potential and two components of the vector potential. The latter is in contrast to the case of cylindrical waves where only one component of the vector potential is needed. The formal solution for the conical wave source goes over to that for the two-dimensional cylindrical wave case in the limit of infinite phase velocity.

C-037 Jette, A.N.; Parker, J.G.
Surface displacements accompanying the propagation of acoustic waves within an underground pipe.
(journal article) J Sound Vibr, 69:2,265-274 (1980).

Theoretical expressions for surface displacements accompanying the propagation of acoustic waves in a buried gas-filled pipe are derived. It is shown that the radiated field consists of both shear and compressional components of comparable amplitude which interfere with one another because of the large difference in the respective propagation velocities. This is manifested at the surface by a series of maxima and minima in the vertical and horizontal displacements. Comparing the theoretical calculation to experimental data on vertical surface displacements generated by plane progressive waves at frequencies ranging from 200 to 2000 Hz within an underground pipe shows that only axisymmetric radial and longitudinal vibration of the pipe wall is important. This stands in marked contrast to experiments carried out by others in air in which the contribution of bending mode excitation was shown to be significant, particularly at lower frequencies. The theory can be fitted to the experimental data only if the compressional and shear velocities α and β, respectively, are narrowly specified, leading to α = 259 m/sec. This value for shear wave velocity is reasonable for clay soil.

APPENDIX A
REPORT OF NEW TECHNOLOGY

This bibliography represents the first time an effort has been made to review the state-of-the-art of the prediction and control of groundborne noise and vibration. The unpublished references in the bibliography are most important in presenting recent techniques used by transit systems in controlling groundborne noise and vibration. Utilization of these techniques will continue to enhance efforts to reduce and control groundborne noise and vibration in the near future.

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