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16. Abstract

This executive digest presents a summary of information contained in the Handbook of Urban Rail Noise and Vibration Control, which is a comprehensive review of the state-of-the-art in the field. The digest is intended for all those who would like an overview of the handbook contents, either as an introduction to the handbook or as a source of information in and of itself. The text provides information useful in integrating noise and vibration control into transit system planning and operations. The tables, following the text, summarize technical information contained in the handbook on control treatments for wayside, vehicle, station, and groundborne noise and vibration.

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PREFACE

This document presents a summary of information contained in the Handbook of Urban Rail Noise and Vibration Control, which is a comprehensive review of the state-of-the-art in the field. The digest is intended for all those who would like an overview of the handbook's contents, either as an introduction to the handbook or as a source of information in and of itself. The text provides information useful in integrating noise and vibration control into transit system planning and operations. The tables, following the text, summarize technical information contained in the handbook on control treatments for wayside, vehicle, station, and groundborne noise and vibration.

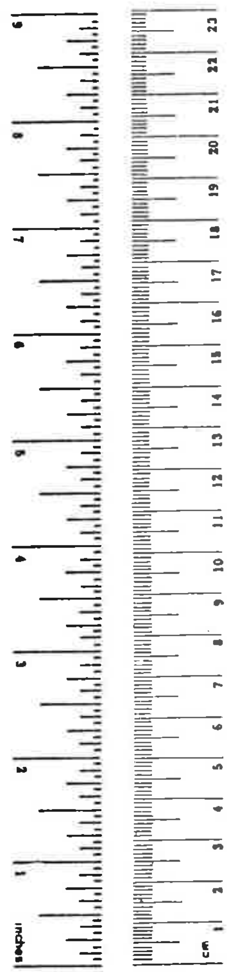
The executive digest and handbook have been prepared by Wilson, Ihrig & Associates (WIA) under contract to the U.S. Department of Transportation. The project is part of the information dissemination activities of the Urban Rail Noise Abatement Program managed by the Transportation Systems Center, Cambridge Massachusetts, under the sponsorship of the Office of Technology Development and Deployment, the Office of Rail and Construction Technology of the Urban Mass Transportation Administration.

The technical effort on this project was coordinated by Michael Dinning of the Transportation Systems Center. Valuable review and comment were also provided by Leonard Kurzweil of Bolt, Beranek and Newman Inc., by Elizabeth Ivey of Smith College, and by Nancy Cooney of Raytheon Service Company. Extensive editorial support was provided by Thayer Williams of Raytheon Service Company.

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



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)		
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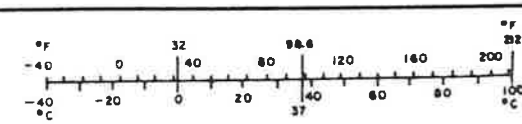

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EXECUTIVE DIGEST

INTRODUCTION

This digest is a summary of the Handbook of Urban Rail Noise and Vibration Control. Information found in the handbook is condensed here for anyone who wants an overview of the subject without having to read the entire document. Although meant for any interested reader, the digest is particularly directed toward transit system managers, engineers, and designers.

Included in the digest is a description of the urban rail transit noise problem, a discussion of noise control criteria and guidelines, approaches to noise control implementation, a description of four main areas of concern - wayside, vehicle, station, and groundborne noise and vibration - and finally, a compilation of specific treatments for noise and vibration problems (included as Appendix A). The treatments, arranged in tables representing wayside, vehicle, station, and groundborne noise and vibration are arranged within each table according to noise source. The tables should enable the reader to perform a preliminary evaluation of the most effective means of controlling transit-related noise and vibration. More detail on treatments is available in the handbook. Appendix B of the digest contains the handbook Table of Contents as a reference.

1. THE URBAN RAIL TRANSIT NOISE PROBLEM

In this age of increased concern about the hazards of environmental pollution, the impact of rail rapid transit noise and vibration is of critical importance. New transit systems are subject to the legitimate concerns of the population, while older facilities are receiving a growing number of complaints about noise. Fortunately, most noise and vibration problems can be controlled at a price that does not sacrifice the facility's main purpose -- moving people.

Excessive noise can definitely cause annoyance and even hearing loss; it may also cause other psychological or physiological trauma. Transit system "noise pollution" can result in complaints, lawsuits, government fines and penalties, and (perhaps most importantly) a loss of public support for rail rapid transit as an alternative to the automobile. Obviously, noise and vibration are problems that cannot be ignored.

2. CRITERIA

In order to determine what type of noise control is appropriate, it is first necessary to establish noise level goals. Such goals vary according to the population exposed (i.e., community residents, patrons, or employees), consideration of local noise ordinances, and special circumstances such as construction activities. For all noise problems, it is important to specify levels that will be acceptable to those exposed, but which at the same time will not be prohibitively expensive or impossible to achieve.

2.1 Community Noise Criteria

Communities may be subjected to both airborne noise and groundborne noise and vibration. Several approaches can be used to determine acceptable levels of exposure. The American Public Transit Association (APTA) Guidelines* offer noise and vibration standards, established by the transit industry as being desirable and practical. The Environmental Protection Agency (EPA) "Levels Document,"** which contains a generalized annoyance curve for noise, may also be consulted. Evaluating complaints and conducting social surveys are also good ways of predicting or evaluating the community response to a noise problem.

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*"Guidelines for Design of Rapid Transit Facilities," Section 2.7, Noise and Vibration.

**"Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety."

For vibration criteria, the APTA Guidelines are recommended as a reference, as are the ISO (International Organization for Standardization) and UITP (Union Internationale de Transport Publique) standards.

2.2 Patron Exposure

Patrons are exposed to noise while waiting for trains and while riding on the trains, but are exposed to significant vibration only while riding in the transit cars. Patron satisfaction and positive attitude are the general rules for rating this type of noise and vibration exposure. In general, patrons in a transit car should be able to maintain a conversation over distances of 3 to 5 feet with normal vocal effort; the subjective rating of car interior noise should be "quiet" at low speeds and "intrusive," but not annoying at high speeds. Standards for patron noise exposure can be found in the APTA Guidelines.

2.3 Employee Exposure

Employee noise exposure is not usually a problem except on older transit systems built without regard for noise control. If a system provides a comfortable acoustical environment for the patrons, then it is unlikely there will be any excessive employee noise exposure. The only times that transit employee noise exposure might exceed acceptable limits on a "quiet" system is in the repair shops and during maintenance and construction activities. OSHA (Occupational Safety and Health Administration) standards are usually applicable to transit system workers under these circumstances. Even on systems where the OSHA standards are not applicable, these noise exposure limits represent reasonable goals and an effort should be made to meet them.

2.4 Local Noise Ordinance

When planning new facilities, it is important to review the impact of any local noise ordinance or regulation. Often, noise from rapid transit construction or operation is not considered when noise ordinances are developed. As a result, strictly interpreted noise ordinances may require a transit system to meet noise limits that cannot, at present, be achieved. For this reason, community understanding of the technical problems faced by transit designers is important, as is a recognition by the transit authorities of local standards for peace and quiet.

2.5 Construction Considerations

Although transit construction noise and vibration are recognized as a temporary problem by most people, they often are a major source of community annoyance. The APTA Guidelines are recommended as a basis for evaluating rail rapid transit construction noise and vibration levels.

In recent years, progress has been made in the control of construction equipment noise and vibration through:

- noise limit specifications in the construction contract documents

- modifying equipment to reduce noise

- basing selection of alternative construction procedures on the resulting noise impact

- requiring that the noise levels be monitored during the construction so that any variation or excess can be immediately rectified.

These efforts have been very successful, and new construction projects are often significantly less noisy than expected.

3. APPROACHES TO NOISE CONTROL IMPLEMENTATION

3.1 Noise Control in System Design and Operation

Noise and vibration control should be considered at several points in the development and operation of a transit facility -- during initial system design, during the preparation of specifications for vehicle and equipment purchase, and during modification to existing facilities and equipment and during maintenance activities. The importance of addressing the problem during design or purchase phases cannot be overemphasized; it is by far the most efficient and economical way of controlling transit system noise and vibration. Nevertheless, it is often feasible to obtain significant reductions on existing equipment and vehicles through economical retrofit procedures. This is particularly true when noise control considerations are included as part of vehicle and facility rehabilitation programs.

The APTA Guidelines include noise and vibration design goals for transit vehicles and structures. Incorporating realistic noise and vibration specifications in the contract documents for new equipment forces the contractor to consider noise and vibration in all phases of equipment design and should result in effective control of equipment noise and vibration. Often, minor design changes, which cause little or no additional expense, result in significant reductions of noise and vibration.

Another cost-effective approach is to achieve noise and vibration control by conducting a comprehensive maintenance program. Maintaining wheels, rails, propulsion systems, and auxiliary equipment in good condition can often substantially reduce levels of noise and vibration. Conversely, excessive noise and vibration often signal mechanical problems in need of attention; thus, noise control and good maintenance often go hand in hand.

3.2 Selecting the Most Appropriate Treatment

In the final analysis, noise and vibration control treatments often represent a compromise. In addition to balancing noise criteria, efficiency, cost, and practicality, it is also important to consider the nonacoustical impact of a treatment and its prospects for being funded.

It is relatively rare for a noise or vibration control feature not to have some impact on other aspects of the system. Sometimes the impact can be positive (e.g., the reduced maintenance costs of welded rail may offset the installation costs), while at other times the impact can be so negative as to negate the benefit gained from reduced noise levels (e.g., enclosures over noisy auxiliary equipment can make maintenance awkward and can result in overheating due to inadequate cooling air). In addition, the availability of funding often depends on whether or not the treatment is a maintenance or a capital expense.

It is clear that these nonacoustical aspects must be carefully weighed in the decision-making process. An effort has been made in organizing the tables to allow consideration at a glance of the major positive and negative aspects of a noise or vibration control treatment. It should, therefore, be possible to ascertain, on at least a preliminary basis, the most appropriate treatments for any given rail rapid transit noise and vibration problem.

4. WAYSIDE NOISE

A principle concern of any rapid transit system is the control of noise and vibration radiated into the community. Available technology makes it possible to control noise at levels acceptable to most people; however, cost constraints often limit the application of acoustical improvements.

Table 1 (see Appendix A) covers most factors that influence wayside noise, including layout and design considerations, new equipment specifications, and retrofit procedures. Covering most important sources of wayside noise, the tabulation includes noise produced by trains, aerial and elevated structures, yards and shops, and ancillary equipment.

4.1 Train Noise

Transit trains are the major source of transit system noise and vibration. The interaction of the wheels and rails, the vehicle propulsion equipment, auxiliary equipment, vibrating structures, and train speed and length are parameters which account for a large percentage of wayside noise and all vehicle interior noise. Because vehicle design and design modifications affect both wayside noise and car interior noise, vehicle noise has been covered separately in detail in Table 2.

4.2 Aerial/Elevated Structure Noise

Aerial structures can be divided into two broad classes - lightweight steel elevated structures and those of higher mass construction. Train operation on lightweight steel structures creates one of the most severe environmental problems facing transit systems. There are many miles of such structures on older transit lines, particularly in New York and Chicago. The rail tie and support structure acts as a large sounding board with very high noise levels radiated to the wayside community and into transit cars. It has proven to be very difficult to achieve significant noise reduction with any practical modifications. However, there is continuing research with the goal of developing practical noise control methods for lightweight steel elevated structures.

The second category of aerial structures are constructed of higher mass materials such as concrete or concrete/steel composite. These structures typically have ballasted trackbeds or concrete decks with resilient rail fasteners. With appropriate noise control treatments, these structures can be placed even in noise-sensitive residential areas without adverse noise impact.

4.3 Ancillary Equipment Noise

It is possible to locate ancillary equipment (fans, fan and vent shafts, substations, and mechanical equipment plants) even in very noise-sensitive areas if suitable control methods are applied.

Designing noise control features for ancillary equipment requires that the maximum sound level ratings permissible be clearly specified. The APTA Guidelines include recommended criteria for ancillary equipment noise. Although it may be more expensive to purchase quiet equipment, this initial incremental cost may actually be less than the cost of acoustical retrofit of equipment at a later date.

4.4 Yard and Shop Noise

Noise from maintenance and storage yards is of a diffenent character than the noise of normal mainline transit train operations or from ancillary facilities. Because of the nature of yard equipment and special trackwork, different design criteria are required to control this noise. However, with the appropriate noise abatement procedures and techniques and with modern transit vehicles, a storage or maintenance yard can be made acoustically acceptable to nearby communities.

Low levels of yard and shop noise can be obtained through the following general considerations: supervision of operating procedures, careful design of yard equipment, use of buffer zones and sound barriers, and controls on transit vehicle operations and equipment.

5. VEHICLE NOISE

Vehicle noise and vibration control can be accomplished by including noise level specifications in the purchase documents for new vehicles or by modifying old vehicles.

If specifications are written into the contract documents, noise controls are less expensive and easier to incorporate into the design and also come with a guarantee. Nonetheless, noise level specifications can be met by modification of old vehicles, using many of the same techniques applied to minimize noise and vibration on new vehicles. Sound level goals for all aspects of transit vehicle noise can be found in the APTA Guidelines.

Table 2 (see Appendix A) lists noise control methods available to reduce exterior and interior vehicle noise. The table indicates when a control treatment is applicable to interior noise and when it will only reduce exterior noise. Also, the table shows the types of noise controls particularly important to consider in the specifications for new vehicle purchases.

6. STATION NOISE

There are four main noise sources in transit stations: trains entering, leaving, and passing through the stations; ancillary equipment, such as HVAC (heating, ventilation and air conditioning) equipment and escalators; crowds; and, in above-ground stations, street or highway traffic and railroads. The principle means of controlling noise in transit stations are the use of sound absorption treatment, careful design of ancillary equipment to meet sound emission criteria, and the use of barriers.

The APTA Guidelines present maximum sound level design goals for station noise. Table 3 (see Appendix A) lists various acoustical treatments available for reducing noise in stations.

7. GROUNDBORNE NOISE AND VIBRATION

Groundborne noise and vibration are caused by vibration at the wheel/rail interface which travels through track and support structure and the intervening soil and rock to nearby buildings. It is experienced as a low-frequency rumbling noise and, sometimes, as a perceptible mechanical vibration. Communities have complained about this problem in areas adjacent to subway, at-grade, and elevated structures, which indicates that controls must be considered for all types of track structures. Current technology makes it possible to virtually eliminate groundborne noise and vibration from any type of transit configuration. However, if the distance from the track to the affected buildings is less than 30 to 50 feet, the requisite control methods may be prohibitively expensive. The prediction and control of groundborne noise and vibration are very complex topics for which there still exists a large number of unanswered questions. Research and development sponsored by the U.S. Department of Transportation is addressing these topics. Table 4 (see Appendix A) lists a variety of treatments appropriate for reducing groundborne noise and vibration.

APPENDIX A

TABLE 1. WAYSIDE NOISE SOURCES AND TREATMENTS

Source: At-Grade Track

TREATMENTS	COMMENTS
A. Maintenance-Related Treatments	
1. Rail grinding	Maintaining rail in good condition is an important step in controlling train noise. Once visible, larger corrugations have been removed, only minor acoustic improvements will be achieved with further grinding.
2. Wheel truing	Wheel truing to remove flat spots and other imperfections from the running surface will significantly reduce wayside noise.
3. General maintenance	Although rail grinding and wheel truing are the maintenance procedures having the greatest impact on wayside noise, keeping cars, rail, and trackbed in good condition will prevent increases in wayside noise.
B. Changes in Train Speed and Length	
1. Reducing train length	Reducing train length during off-hours, particularly nighttime, could reduce community annoyance. However, if the frequency of train operations is increased to compensate for reduced train length, the benefits will be negated.
2. Reducing train speed	Reducing train speed to help control community annoyance with transit noise is an undesirable approach. Its limited benefits are usually outweighed by the added cost and lost time.
3. Scheduling	In most cases, there is relatively little that can be achieved with scheduling modifications. If several types of transit vehicles are available, some benefit could be gained by running the quietest type during nighttime hours and concentrating them on lines in noise-sensitive residential areas.
C. Other Treatments	
1. Sound barriers	Barriers may consist of walls, earth berms, sides of depressed cuts, or edges of buildings. Any object breaking the line-of-sight between the train and the receiver will act as a barrier against sound. As a rule of thumb, 5 dBA attenuation is easy to obtain; 10 dBA can be achieved with careful attenuation to barrier design; 15 dBA is usually the outside limit. Once vehicle design, route alignment, and structure configuration have been determined, sound barriers are often the only viable alternative for further reduction of wayside noise.
2. Trackbed absorption	Noise levels adjacent to ballast-and-tie track are 2 to 5 dBA lower than those adjacent to a concrete trackbed due to the acoustically absorbent property of ballast. Absorbent material (e.g. fiberglass) can be added to a concrete invert trackbed, resulting in a 2 to 5 dBA reduction in noise level. In revenue service, however, the material tends to become rapidly contaminated with dirt and brake dust, rendering it ineffective.

Source: Aerial/Elevated Structures

TREATMENTS	COMMENTS
A. Treatments for All Elevated Structure Types	
1. Reducing wheel/rail forces	
a. Rail grinding and wheel truing	Maintaining wheels and rails in good condition without discontinuities, corrugations, flat spots, etc., is an important step in controlling the vibrational energy transmitted to the aerial structure.
b. Resilient wheels	The resiliency reduces the effective mass "seen" by the rail and hence reduces the vibrational force on the rail.
c. Welded rail	Impacts at joints increase the vibrational energy flowing into the aerial structure. Welding rail ends together will eliminate this source of vibration, but rail expansion and contraction during welding may put excessive stress on the aerial structure.
d. Truck modifications	The truck suspension can have an effect on the vibrational energy that flows into the structure. Reducing the primary suspension stiffness can reduce structure-related noise at some frequencies.
2. Track and Invert Vibration Isolation	
a. Resilient fasteners	Resilient fasteners with stiffness less than 200,000 lb/in. will reduce any structure-radiated noise above approximately 200 Hz.
b. Resiliently supported ties	Although more commonly used in subways, resiliently supported ties could be effective on aerial structures, more so on concrete deck structures than on lightweight steel structures.
c. Ballast	Using ballasted track on a concrete deck or a steel elevated structure will provide some vibration isolation and damping of the structure. Additional benefits are the reduction of vibration due to the increased mass and the reduction of acoustic absorption properties of ballast. The primary disadvantages are the cost of installation, the added stress on the structure, and the increase in track maintenance relative to direct fixation.
d. Ballast mats	On ballasted elevated structures where noise radiation from the structure is a problem, ballast mats have been shown to provide significant attenuation above approximately 200 Hz. Ballast mats are also used to control pulverization of ballast.
e. Floating slabs	A vibration isolation floating slab could be designed to control noise radiated from the aerial structure. Rarely would such an extreme measure be required or used.
3. Damping of Noise-Radiating Components	
a. Viscoelastic damping	Viscoelastic materials are attached to the structural components radiating the most noise - usually by means of a metal restraining plate.

The material reduces the amplitudes of vibrational energy by transforming it into heat. The frequency range over which damping is effective is determined by the characteristics of the damping material and the thickness of the restraining layer. In order to be effective, damping treatments must be applied to all major noise-radiating components.

A wide assortment of damping materials are available to meet the requirements of specific problems.

b. Addition of mass

Increasing the mass of a vibrating body will reduce the amplitude of vibration and hence the radiated noise. At high frequencies, the amplitude of vibration is inversely proportional to changes in mass, i.e., doubling the effective mass will reduce amplitude by a factor of 2.

Increasing mass is feasible for specific components. For example, the increased mass of a concrete deck helps reduce structural vibration. While increased mass is a realistic consideration in the design of new structures, it is rarely appropriate for retrofit applications.

c. Increasing stiffness

For specific cases, increasing the stiffness of vibrating components will reduce amplitudes of vibration and hence levels of radiated noise. The effect of changing the resonance frequencies must be carefully evaluated to ensure that the result is an improvement.

d. Reduction of radiating area

The sound energy radiated by a vibrating body is approximately proportional to the surface area of the body. Hence, decreasing the surface area will reduce the amount of sound radiated. The reduction of the radiating area is, however, a realistic consideration for new designs only.

4. Shielding

a. Sound barrier walls

Sound barrier walls on aerial structures work in the same manner as sound barriers for at-grade track (see Source: At-Grade Track, C, 1).

Sound barriers are primarily effective on structures with concrete or ballasted decks where the train, the wheels, and the rails are the primary noise sources. For steel elevated structures where the structure itself radiates a significant amount of noise, barriers are not particularly effective.

In some cases, the vibration of the barrier can become a major noise source. Resiliently mounting the barrier to the elevated structure will control this problem.

b. Acoustic pans

Acoustic pans are special shields which enclose the bottom of the structure in order to control structure-radiated noise. The shield must be resiliently mounted to the structure to be effective. Acoustic pans are appropriate for steel elevated structures where the structure itself is a significant noise source.

Although an unwieldly solution to this problem of structure-radiated noise, JNR (Japanese National Railway) tests have demonstrated dramatic reductions in structure-radiated noise with this technique.

TREATMENTS	COMMENTS
B. Lightweight Steel Elevated Structure Treatments	
1. Welded rail	See A, 1, c.
2. Use of resilient fasteners	See A, 2, a.
3. Addition of a concrete deck	A concrete deck adds mass and increases damping, thus reducing structure-radiated noise. Most steel elevated structures, however, are not strong enough to take the added weight of a concrete deck.
4. Addition of ballast	Ballast reduces structure-radiated noise due to increased mass and damping. In addition, the acoustic absorption properties of ballast reduce the levels of wheel/rail and propulsion equipment noise. Ballast is added to the structure by placing it in a concrete or steel pan. Most lightweight steel structures, however, are not strong enough to take the added weight of ballast.
5. Viscoelastic damping	See A, 3, a.
6. Shielding (Sound barriers and acoustic pans)	See A, 4, a and A, 4, b. To be effective all important sources of noise radiation must be shielded from the receiver. Such complete shielding is often impractical because of cost and the inability of the structure to carry the extra weight.
C. All-Concrete Structure Treatments	Treatments for all-concrete structures are essentially the same methods as for at-grade track, i.e., welded rail and wheel/rail maintenance, resilient fasteners, sound barrier walls, and absorption material on deck or sound barrier walls. With appropriate treatments, this type of structure can be placed in quiet residential areas without excessive noise impact.
D. Composite Steel/Concrete Structure Treatments	With the exception of the potential for low-frequency noise radiated from the steel girder, these structures are the same as all-concrete structures. Constrained layer damping can be used to control this low-frequency vibration.

Source: Yards and Shops

TREATMENTS	COMMENTS
A. Choosing Optimum Location and Layout	
1. Layout	Yards and shops may be located so that noise-producing activities are shielded from adjacent communities by natural topography. Such shielding also reduces visual impact.
2. Buffer space	Purchasing extra land around yards and shops to act as a buffer space can reduce noise, but this is often an expensive solution.
3. Sound barriers	Sound barriers and earth berms are an effective method of controlling most yard and shop noises. They reduce visual impact as well as acoustic impact.

TREATMENTS	COMMENTS
B. Vehicle Noise	
1. Reducing wheel/rail noise	
a. Resilient or damped wheels	Resilient or damped wheels are used primarily for control of wheel squeal although there is some reduction of other noises as well.
b. Rail lubrication	Rail lubrication is used in yard areas to reduce wheel squeal and excessive wear on wheels and rails. Although it can be effective at reducing wheel squeal, wheel flats caused by lack of traction can be a problem.
c. Wheel/rail maintenance	See Source: At-Grade Track, A, 1 - A, 3.
2. Reducing auxiliary equipment noise	Auxiliary equipment noise of idling trains is often a principal complaint of adjacent communities. If trains must idle for significant periods of time, they should be kept in areas shielded from the community.
C. Reducing Shop Activity Noise	
1. Confinement of activities	Where possible, activities should be confined to the interior of maintenance and inspection shops. Activities which must be conducted outdoors should be well removed from the adjacent community.
2. Use of absorption materials on shop interiors	Shop building should include absorption materials on building interior surfaces to control reverberant noise.
D. Reducing Car Wash Noise	
1. Enclosure	Completely enclose car wash in a building.
2. Location	Locate in areas well removed from adjacent residential or other noise-sensitive areas.
3. Absorption material	Absorption material can be used on inside surfaces of car wash building. The absorption material must be waterproof (e.g., sound-absorbing structural masonry units or tiles).
E. Alternatives to Buzzers, Horns, and Loudspeakers	
1. Substitution of light signals	Light signals may be used in lieu of audible signals. Because of safety requirements, however, train horns can never be completely eliminated. Other alternatives include the use of windows to increase visibility and specific operating procedures that minimize the need for warning signals.
2. Use of melodious horns	Melodious horns can be used instead of air horns or rancorous electronic horns and buzzers. These horns are relatively nonintrusive in neighboring areas.

Source: Ancillary Equipment Noise

TREATMENTS	COMMENTS
A. Reducing Fan and Vent Shaft Noise	
1. Use of acoustical absorption material	Acoustical absorption material can be applied to surface of fan rooms and shafts, and on tunnel walls and ceilings near shaft entrances.
	It is most effective to line bends rather than straight ducts (before and after 90° bends).
	Absorption materials must be durable and economical; they must provide efficient sound absorption in the frequency range covered by the 500 Hz and 1000 Hz octave bands, and adequate sound absorption in the remaining frequencies.
	Although many acoustical materials will not satisfy fire safety requirements, there are commercially available products that satisfy the most restrictive requirements.
	Acceptable types of sound absorption material include spray-on materials, glass-fiber boards or blankets, and cellular glass blocks.
a. Spray-on material	Spray-on materials are easy to install and are cheaper than glass-fiber materials.
b. Glass-fiber boards and blankets	Glass-fiber boards and blankets have the highest sound absorption coefficient. They can be mechanically attached to the fan and vent shaft interior surfaces where mechanical protection of the material is necessary. The installation may include an outer covering of acoustically transparent materials, such as hardware cloth, expanded metal, or perforated sheet metal.
	Dust or dirt collecting on surface of glass fiber will not affect sound absorption characteristics. Water has no permanent effect although absorption is reduced while the material is actually wet.
c. Cellular glass blocks	Geocoustic blocks are inorganic and incombustible, however, they also shed small glass granuals. If used overhead in public areas, the possibility of shedding problems should be investigated. They have been successfully used in several transit applications.
2. Attachment of sound attentuators to fans	A number of factors should be considered when selecting an appropriate attenuator. Prefabricated attenuators are available in both rectangular and round shapes so that either a conical outlet cone or a round to rectangular sheet metal transition can be used on fans. Round units are generally less desirable because of space requirements. Other factors to be considered in selecting an attenuator include the maximum permissible head loss and the airflow velocity of the operating unit.
	Attenuators are also referred to as silencers, mufflers, and sound traps.

TREATMENTS	COMMENTS
B. Reducing Fan Room Noise	
1. Use of acoustical absorption material	When a fan room acts as an intake or discharge plenum, significant noise reduction is possible through lining the fan room with acoustical treatment. When axial fans are installed in ducts leading out of the fan room, sound absorption material inside the fan room will not help reduce external noise levels. It will, however, reduce noise inside the fan room and help protect maintenance personnel. In order to reduce noise discharged through ducts, noise control treatments must be installed inside the ducting system.
C. Treatments to Above-Ground Substations	
1. Surround with high walls	Any openings in walls should face non-noise-sensitive areas (e.g., toward street).
2. Buffer space	Many times, substations can be located in a sufficiently isolated area such that additional sound control is unnecessary.
3. Noise level specifications for new purchases	Both the noise from the transformer hum and the noise from the cooling fans must be considered.
D. Reducing Mechanical Equipment Room Noise	The chiller is the largest, usually most powerful, and hence noisiest piece of equipment, although other pieces of noisy equipment include fans, pumps, and compressors.
1. Installation of acoustical material	Acoustical absorption material can be installed inside the mechanical equipment room to reduce the reverberant sound level inside the room.
2. Sealing cracks	Cracks around doors or other locations can be sealed with gasket material or resilient, nonhardening caulking material.
3. Change location	The site of the room can be changed to a less noise-sensitive location.
4. Change orientation	The orientation of the room can be changed so that the noise will radiate towards the street.
5. Barriers	Barriers or baffles can be placed between any opening in the equipment room and the receiver.
6. Sound traps	Sound traps or acoustical louvers can be installed to reduce noise transmitted through openings in the enclosure.
7. Quieter equipment	Equipment that produces lower noise levels can be selected.
E. Reducing Cooling Tower Noise	Noise levels expected from cooling towers should be based on sound level data supplied by the manufacturer.
1. Orientation of tower	Information on the directivity of cooling tower noise is important. Most towers are directive, with the highest noise levels radiated from the fan or nozzle sides. Knowledge of the directivity of the radiated sound allows the tower to be oriented in such a way that the highest levels of sound are directed towards the least noise-sensitive areas.

TREATMENTS	COMMENTS
2. Barrier walls	Parapets or barrier walls high enough to block the direct line-of-sight of the cooling tower from receiver location can be installed.
3. Use of centrifugal fan towers	Centrifugal fan towers create significantly less low-frequency noise than propeller fan units. At high frequencies, the noise from the two types of units is comparable. Sound barrier walls can effectively reduce the high-frequency noise.
4. Use of ejector cooling towers	Although ejector cooling towers produce less low-frequency noise than centrifugal fan units, their high-frequency noise is comparable. Since silencers are not available for ejector units, further noise reduction will require sound barrier walls or similar treatments.
5. Use of packaged attenuators	Packaged attenuators can be used in the air inlet and exhaust openings. They are available from cooling tower manufacturers and some muffler manufacturers. It is not usually possible to install attenuators on ejector units.
6. Reducing fan speed	Fan motor speed can be reduced when the cooling load is reduced. Operating the fans at reduced speed will produce a 6 to 10 dB reduction of fan noise.

TABLE 2. VEHICLE NOISE SOURCES AND TREATMENTS

Source: Wheel/Rail Noise

TREATMENTS	COMMENTS
A. General Treatments	
1. Rail grinding	Although rail grinding does not involve the vehicle, it is an important component of any program to reduce wheel/rail noise. It is particularly important for controlling noise from corrugated rail.
2. Wheel truing	Maintaining wheels in good condition with a minimum of flats will significantly reduce wayside and car interior noise.
3. Long side skirts	Since wheel/rail noise originates under the car, long side skirts can significantly reduce all types of wheel/rail and propulsion equipment noise. Disadvantages include interference with accessibility for maintenance and possible reduction of airflow for cooling traction motors. Properly designed side skirts can reduce drag on the vehicle.
4. Undercar absorption	Undercar absorption can act to absorb wheel/rail noise before it is radiated to the wayside or through the floor into the car. It is particularly effective in combination with long side skirts.
B. Treatments for Roar Noise	
1. Rail grinding	See A, 1. Although rail grinding will not dramatically reduce noise levels if the rail is already in good condition, it is an important standard maintenance feature for all track.
2. Wheel truing	See A, 2.
3. Resilient wheels	Resilient wheels may reduce roar noise, however, most test have not shown significant noise reduction.
4. Damped wheels	As with resilient wheels, damped wheels may reduce roar noise, however, the reductions do not appear significant.
5. Slip-slide detectors	Slip-slide detectors or nonskid braking systems can be effective at reducing imperfections on the wheel surface. This reduces the occurrence of wheel flats. Wheel flats increase the levels of both roar and impact noise.
C. Treatments for Impact Noise	
1. Improved rail	Although this is not a car modification, it is an important component of controlling impact noise. Included in this category are rail grinding, adjusting joint bars to reduce gaps, ballast dressing to minimize tie movement, changing to welded rail, using bonded insulated joints, and use of smooth transition rail joints.
2. Wheel truing	An important reason for wheel truing is to remove wheel flats that cause impact noise. Wheel truing should be included in any car maintenance program.
3. Resilient wheels	There is no positive evidence that resilient wheels will significantly reduce impact noise on U.S. transit systems.
4. Damped wheels	As with resilient wheels, damped wheels do not appear effective at reducing impact noise.

TREATMENTS	COMMENTS
5. Slip-slide detectors	Slip-slide detectors or nonskid braking can virtually eliminate the occurrence of wheel flats. This can result in a very significant improvement in the car interior and wayside acoustical environment.

D. Treatments for Squeal Noise

TREATMENTS	COMMENTS
1. Minimize short-radius curves	Clearly, reducing the number of short-radius curves will reduce the occurrence of wheel squeal. A general rule of thumb is that squeal will not occur on curves with radii greater than 100 times the truck wheel base.
2. Rail lubrication	Lubricating rails with grease or water can significantly reduce wheel squeal. Rail lubrication is used on many transit authorities. If the lubricant reaches the top of the rail, the reduction of wheel/rail traction can cause slippage and the formation of wheel flats.
3. Resilient wheels	Most resilient wheels will virtually eliminate squeal noise. Recent testing, however, has shown that resilient wheels may not be compatible with tread braking systems. Brake overheating can cause the bond between the elastomer and the wheel to fail.
4. Damped wheels	Damped wheels are also very effective in eliminating wheel squeal. Types of damped wheels include ring-damped, viscoelastic-damped , and tuned-damped wheels. Ring-damped wheels appear to be one of the most cost-effective methods of controlling wheel squeal. They have been found to virtually eliminate squeal noise at frequencies above 1500 Hz.
5. Articulated trucks	Articulated or steerable trucks can eliminate wheel squeal by steering instead of "crabbing" around curves. These trucks are still in the experimental stage.
6. Rail grinding	Rail grinding has little effect on wheel squeal.
7. Wheel truing	Wheel truing produces only marginal reductions in wheel squeal.
8. Conical wheels	Although conical wheels in place of cylindrical might be expected to create less wheel squeal, the difference does not appear significant.
9. Hardfacing rail	Hardfacing rail, a process in which very hard, low-friction steel strips are welded onto the rail head, has shown promise as a method for controlling wheel squeal when used on an experimental basis in Germany.

Source: Propulsion Equipment

A. General Treatments

TREATMENTS	COMMENTS
1. Long side skirts	See Source: Wheel/Rail Noise, A, 3. Because the sources of propulsion equipment noise are under the car, side skirts are effective in reducing wayside noise levels.
2. Uncercar absorption	See Source: Wheel/Rail Noise, A, 4. Undercar absorption can decrease wayside noise levels especially when used in conjunction with long side skirts. The absorption will reduce car interior noise as well.

TREATMENTS	COMMENTS
B. Treatments for Cooling Fans on Self-Ventilated Motors	Self-ventilated motors have cooling fans attached to the motor shaft. These fans are one of the major sources of car interior and wayside noise. Noise levels can be significantly reduced by using ducted forced air cooling rather than self-ventilation.
1. Randomly spaced blades	Evenly spaced fan blades create a strong pure tone at the blade passage frequency. Using randomly spaced blades will reduce the pure tone component.
2. Redesign of fan	Fans may be redesigned to be similar to axial vane type fans. However, cooling may not be as effective as with normal radial fans. Fans might also be designed with a wide wheel and backward or forward curved airfoils. It is questionable how effective this approach would be at reducing noise.
3. Enclosure of traction motor	High transmission loss (sound insulation) enclosures around traction motors are an effective, but usually undesirable solution for noise problems because of difficulties with maintenance access and insufficient cooling.
C. Treatments for Ducted, Forced Air-Ventilated Motors	Ducted, forced air ventilation is an inherently quieter system than self-ventilated motors. However, poorly designed forced air ventilation can be as noisy as self-ventilated motors. A significant advantage of forced air ventilation is that there is a continuous flow of cooling air, even after the train stops. A disadvantage is that the fan noise continues when the train stops.
1. Enclosure of fans	High transmission loss (sound insulation) enclosures built around the fans will control noise radiated directly from the fans.
2. Acoustical treatment of air ducts	Lining air ducts with standard duct liner absorption material will reduce fan and air turbulence noise transmitted along the ducts.
3. Silencers	In extreme cases where lining ducts will not sufficiently control the fan noise, small duct silencers (also referred to as sound traps, attenuators, or mufflers) can be used. They are rarely used, however, on transit cars.
D. Treatments for Other Motor Noises	
1. Redesign of motors	Since noise levels are dependent on basic motor configuration, significant reduction generally requires basic design changes. These noises are, however, generally not high enough to be a problem.
2. Enclosures	An enclosure could be designed to reduce the levels of these noises, however, it is generally an impractical solution.
E. Treatments for Gear Noise	Gear noise can be reduced through the use of hypoid gear sets. Hypoid gears, inherently quieter than gear and pinion arrangements, can be specified in the procurement specifications.

Source: Auxiliary Equipment

TREATMENTS	COMMENTS
A. Treatments for Choppers	Chopper systems are more energy efficient than cam control systems, however, they can create annoying pure tone noise inside the cars at low speeds. Ways to reduce chopper noise include vibration isolation, full or partial enclosure of the chopper reactor unit, and extra floor insulation in the area where the chopper reactor unit is mounted.
B. Braking System Treatments	
1. Nonsquealing brakes	There is no "off-the-shelf" treatment for squealing brakes. Brakes which generate a significant amount of squeal should be redesigned by changing the stiffness of the mounting system, by use of a damping treatment, or some other method.
2. Mufflers	Mufflers can control the noise of air dumping or discharges from the braking system. Air discharges can be significant noise sources in stations and yards.
C. Air-Conditioning/Air-Handling System Treatments	The major components of air conditioning on a transit vehicle are the compressor, condensor, and evaporator. These units, if not properly designed and treated, can generate low-frequency noise inside the transit car. The following are ways to reduce noise and vibration from air-conditioning systems.
1. Increase coil area	Increasing the coil area will allow for reduced fan speed for an equivalent airflow and heat transfer. Reduced fan speed will result in less fan noise.
2. Substitute shear mounts	Use shear mounts in place of resilient plate form mounts for equipment under the car. The shear mounts usually have a lower stiffness, hence the vibration isolation is improved.
3. Reposition evaporators	Position evaporators under car rather than above the ceiling or in the wall. This will result in lower car interior noise levels.
4. Acoustically treat air ducts and plenums	Air ducts and plenums can be lined with acoustical material.
5. Minimize air turbulence and flow velocity	Unnecessary bends in ducts increase air turbulence and flow velocity. The use of large cross-section ducts can avoid this problem.
6. Check natural frequencies	Make certain that natural frequencies of any cover panels and refrigerant lines are different from compressor and fan rotational frequencies.
7. Avoid use of noisy fans	Avoid steep propeller blade fans and high-speed radial blade centrifugal fans which produce high noise levels.
8. Keep motors and fans in proper balance	Pay particular attention to proper balance of all motors and fans. Mechanical imbalance limits and performance tests should be included in purchase documents.
D. Treatments for Motor Alternator and Low Voltage Power Supply	Transit cars have either a motor alternator or a low voltage power supply to provide power to the car's auxiliary systems. Ways to reduce noise from either of these sources include enclosure of units, acoustical treatment on the inside faces of enclosure walls, and vibration isolation of unit components or the entire unit.

TREATMENTS	COMMENTS
E. Treatments for Equipment Cooling Blowers	Equipment cooling blowers create noise similar to that produced by traction motor cooling fans, discussed previously. Noise levels can be reduced by avoiding noisy fans (high-speed radial blade and centrifugal fans) and by acoustically treating cooling ducts.
F. Overhead Fan and Blower Treatments	The overhead blowers used for ventilation of some older transit cars are extremely noisy when operating at maximum speed. Treatments for overhead fans and blowers include reduction of fan speed, use of quieter types of fans, replacement of worn bearings, vibration isolation of fan motor, and acoustical lining of ducts.
G. Treatments of Miscellaneous Auxiliary Equipment (Various Fans and Blowers)	Units should be well-balanced, and properly designed and mounted. They should be placed where there is no direct path for noise to travel from the unit into the car. In order to keep fans and blowers in good condition and to reduce noise, rotating elements should be rebalanced, worn bearings replaced, and equipment lubricated on a regular basis.
H. Car Door Treatments	
1. Sliding door treatments	Sliding doors open by traveling along a track into a pocket in the car wall. These doors generate significant impact noise when they unlock and when they close. This noise can be reduced through better insulation of door lock actuators and use of a more resilient rubber channel to cushion the impact of door closings.
2. Plug door treatments	Plug doors open by sliding along a track outside the vehicle wall. Like sliding doors, plug doors create impact noise when unlocking and when closing. Treatments are the same as for sliding doors.
3. Bi-fold door treatments	Bi-fold doors have hinged sections which allow the doors to fold back and open. Because of the hinged sections, bi-fold doors allow more sound leaks than sliding or plug doors. Also, their lighter weight construction provides poorer sound insulation. They are not often used on new cars because they fail to meet access requirements of the disabled.
I. Lighting System Noise Treatments	The lighting system of most new transit vehicles consists of fluorescent lamps with associated ballast. Improper installation of ballast or the use of noisy ballast can give rise to a pure tone hum annoying to passengers in the car.
J. Public Address System Treatments	The public address system should be free of hum and noise. A noise-cancelling type of microphone should be used so that car interior noise is not amplified during announcements.

Source: Sound Transmission of Car Body Components

TREATMENTS	COMMENTS
	At speeds in excess of 50 km/hr (30 mph) noise from the air-conditioning system and other auxiliary sources is dominated by propulsion system noise and wheel/rail noise. Since both of these sources are outside of the car shell, the transmission loss or sound insulation of the floor, walls, and doors determines the interior noise of the car operating at high speeds.

TREATMENTS	COMMENTS
	In order to reduce noise levels, the sound insulation of all car body components must be considered. Poor sound insulation of one component will negate advantages of high sound insulation of other components.
	The sound insulation of the floor is the most important characteristic for surface or elevated operations, since the dominant noise sources are located beneath the floor. The sound insulation of the walls, doors, and ceiling are more important for subway operations where the sound field surrounding the entire car is at a higher level.
	Including specifications for minimum sound insulation of specific car body components in new car procurement, contracts ensure that acceptable noise levels can be achieved inside the cars.
A. Floor Treatments	
1. Use of composite floors	Composite floors are often required for fire safety. If properly designed, they can also provide very effective sound insulation.
2. Seal penetrations	Air leaks caused by penetrations through the floor for seat attachment, cables, etc., will significantly reduce the sound isolation effectiveness of the floor. Penetrations can be sealed with resilient caulking material.
3. Addition of lead vinyl laminate	A layer of lead vinyl laminate or similar material under the carpets will significantly improve the sound isolation of a lightweight floor.
B. Wall and Ceiling Treatments	
1. Absorption material	Standard thermal insulation materials will provide the necessary acoustical absorption.
2. Seal penetrations	See A, 2.
3. Change thickness or material used in walls	Sandwich wall construction - two impervious layers separated by a layer of sound absorption material - provides the best sound insulation. In order to achieve maximum sound insulation, the two layers should be of different thicknesses or materials.
4. Increase gap between inside and outside wall	When the separation between the walls is too small, the sound insulation properties of the wall are diminished.
C. Window and Door Treatments	
1. Improve seals	The air leaks around doors and windows are often the weakest link in the car body's sound insulation.
2. Increase thickness	Increasing the thickness of the window material will increase the sound insulation.
3. Use of laminated material	Laminating two different thicknesses of glass or plastic with an elastomeric damping material will give a higher sound insulation than an equivalent thickness, single layer of the same material.
4. Seal windows and provide forced air ventilation	Open windows provide an excellent sound transmission path. Even closed operable windows often provide a good path for sound to enter the car. Use of forced ventilation and nonoperable windows, now standard in most new transit cars, is the best way to prevent sound transmission through windows.

Source: Vehicle Vibration

TREATMENTS	COMMENTS
A. Vehicle Design	Standards for vehicle vibration should be included in vehicle procurement contracts.
1. Primary springing	Relatively few truck design parameters have a significant effect on noise. However, noise levels appear to be lower on trucks that have primary springing.
2. Soft journal sleeves	On trucks without primary springing, rubber journal sleeves can give the same effect.
3. Rubber bushings	Rubber bushings can be used to eliminate metal-to-metal contact. The rubber bushings interrupt vibration transmission paths through the truck and increase the damping in the truck.
B. Ancillary Equipment Treatments	
1. Balance of rotating parts	All equipment with rotating parts should be maintained in good balance.
2. Reduce mass of rotating parts	The forces caused by rotating components are directly proportional to the mass of the components.
3. Vibration isolation mounts	Most rotating pieces of auxiliary equipment require vibration isolation mounts. Shear type mounts can provide more effective vibration isolation than compression mounts.
4. Avoid coincidence of panel resonances and rotational frequencies	An example of such a coincidence would be a floor resonance which matched the rotational frequency of a compressor mounted beneath the floor. In such a case, vibration amplitudes could build up in spite of vibration isolation mounts.

TABLE 3. STATION NOISE

Source: Train Operation

TREATMENTS	COMMENTS
A. Acoustical/Absorption Treatment	The use of absorption treatment in transit stations prevents excessive buildup of reverberant noise and substantially reduces noise levels. In addition, it helps to reduce crowd noise, exterior noise transmitted through entrances and shafts, and mechanical equipment noise. The intelligibility of the public address system is also improved.
1. Placement of acoustical material	In underground stations, acoustical materials should be installed in underplatform areas, in platform walls and ceilings, and in enclosed concourse spaces such as fare collection areas, stairs, escalators, and corridors. Similarly, enclosed areas of above-grade stations should have ceiling- and wall-mounted absorption treatment. Absorption material must be placed close to the noise source so that sound energy can be absorbed before it reaches the reverberant sound field.
2. Types of acoustical treatments	There is a wide variety of acoustical materials that can be used to treat transit stations. The choice of material is based on the amount of absorption that is required, architectural considerations, ability to withstand the pressure transient loading in stations, resistance to mechanical loading in stations, resistance to mechanical abuse, safety considerations, cost, and other factors. One very important consideration is the fire rating of the acoustic treatment. The material <u>must</u> meet all of the safety standards, including fire and smoke ratings.
a. Glass wool or glass-fiber boards and blankets	Glass wool or glass-fiber boards and blankets are available in a number of different forms including semi-rigid and rigid boards. Binder material is flammable; nonflammable configurations of glass wool are available which use no binder material at all. A disadvantage of glass-fiber material, particularly the nonflammable products, is that a protective or retaining covering or facing is generally required. Facings are needed for protection of glass fiber in subway station applications. To prevent accumulation of dust and to permit washing, glass fiber should be enclosed by a wrapping. The covering slightly decreases the high-frequency sound absorption of glass fiber and slightly increases the mid- and low-frequency sound absorption. The net effect is a slight improvement in sound absorption. Plastic film used as a protective covering does not always meet fire resistance requirements. Closeweave glass-fiber cloth can be used as a substitute.
b. "Geocoustic Blocks"	These blocks, manufactured by Pittsburgh-Corning, are noncombustible and require no protective covering or facing. The material is rigid and self-supporting, and is typically held in place with an adhesive such as epoxy.

TREATMENTS	COMMENTS
	One disadvantage is that the blocks are relatively fragile; they should not be used in any location subject to mechanical abuse.
c. "Soundblox"	"Soundblox" are concrete blocks with slots designed to make the hollow core of the block act as a sound absorber. Hollow ceramic tiles with the same sound absorption mechanism are also available. Since these units are made of concrete or tile, they are relatively impervious to mechanical damage and vandalism. They can be used as structural units.
B. Other Treatments	
1. Ballast	The ballast in ballast-and-tie track provides a significant amount of acoustic absorption, and when used in stations can reduce noise levels.
2. Sound barriers	On side platform stations, further reduction can be achieved with sound barriers to block noise from far-track trains.

Source: Highways and Railroads

TREATMENTS	COMMENTS
	The platform area of surface stations are sometimes exposed to noise from traffic or railroads. Although railroads cause intermittent high noise levels and traffic noise is more continuous, the methods of controlling the noise are basically the same.
	Criteria for appropriate levels of traffic noise are determined by those appropriate for residential areas near highways, the need for speech communication between patrons, and the need for intelligibility of public address system announcements.
1. Sound barriers	The general rule is that the further the sound barrier is located from the platform, the higher it will need to be to produce a given degree of noise reduction.
	Regardless of economic or architectural considerations, the acoustic barrier wall must extend beyond the platform end in order to reduce noise at all locations on the platform (usually about 30 m beyond the end of the platform).
2. Acoustical treatment of platform roofs	Acoustical materials can be applied to platform roofs of above-grade stations to minimize reflections.
	In addition, careful shaping of the roof can minimize the reflection downward and prevent focusing of traffic noise onto the platform.

Source: Ancillary Equipment in Stations

TREATMENTS	COMMENTS
A. Treatments for Ductborne Noise	Ductborne transmission is a main source of noise intrusion in public areas. This noise can be reduced by locating ducts away from public areas and by proper selection of equipment. Vibration isolation of fans, pumps, compressors, and connecting elements, and the provision of sound attenuators and lined ducts may also be necessary.

TREATMENTS	COMMENTS
B. Ventilation Fan Treatment	Ventilation fan treatments include installation of sound absorbent materials in fan room, attenuators on the fan intakes and/or discharges, and sound insulating doors at the machinery rooms.
C. Escalator and Door Treatment	Specifications in equipment purchase documents can insure that escalator and door noise is comparable to typical background noise in stations.
D. Transformer Treatment	Transformers should be installed in separate rooms away from public areas. Transformer room doors should have proper sound insulation (e.g., metal doors with weatherstripping).

TABLE 4. GROUNDBORNE NOISE AND VIBRATION

Source: Surface Irregularities

TREATMENTS	COMMENTS
A. Treatments for Wheel Roughness and Flats	
1. Wheel truing	Periodic wheel truing minimizes roughness and removes wheel flats, thereby reducing groundborne noise and vibration, as well as wayside and car interior noise. Wheel truing is cost-effective because it is usually part of standard maintenance.
2. Slip-slide detectors	Slip-slide detectors can virtually eliminate wheel flats.
3. Wheel flat detectors	TTC (Toronto Transit Commission) has installed a wheel flat detector that automatically identifies cars with significant wheel flats.
4. Resilient wheels	It has been claimed, but not proven, that resilient wheels reduce the occurrence of wheel flats.
B. Treatments for Rail Roughness and Discontinuities	
1. Rail grinding	Rail grinding, now used by most transit systems to control wheel/rail noise, is also essential for controlling groundborne vibration from rail corrugations.
2. Jointed rail treatments	
a. Welded rail	Welded rail is strongly recommended for all new track or wherever extensive trackwork is planned. The higher installation cost is usually balanced by reduced maintenance costs.
b. Rail grinding	Rail grinding can be used to reduce vertical misalignment. Grinding will also reduce noise due to rail roughness, but this usually produces only minor reductions of groundborne noise and vibration.
c. Adjustment of rail bars	Adjusting and/or tightening joint bars can reduce joint misalignment. Reduction of groundborne noise and vibration will be noticeable only in cases where joint misalignment can be significantly reduced.
3. Special trackwork treatments	
a. Placement of trackwork	Special trackwork can be placed in areas not sensitive to groundborne noise and vibration. This is a consideration for initial system design and system expansion.
b. Floating slabs	Some systems (e.g., TTC, WMATA, MARTA) place all subway crossovers on floating slabs except in areas where there is no potential of groundborne noise and vibration problems.
c. "Gapless" frogs	Gapless frogs and other specially designed trackwork can be used to reduce impact, but have not been widely used in the U.S. because of the added cost and potential maintenance problems.

Source: Vehicle Vibration

TREATMENTS	COMMENTS
A. Truck Design	
1. Reduce primary suspension stiffness	There is growing evidence that the primary suspension resonance can strongly influence groundborne noise and vibration. Maintenance of the primary suspension resonance below 10 to 12 Hz means that the effective interaction between the truck suspension and the track support system will be reduced (especially floating slabs). Although reducing the primary stiffness is difficult or impossible on many existing trucks, it can sometimes be accomplished with modifications to the rubber journal sleeves.
2. Install vibration dampers	Although it has been conjectured that vibration dampers could be designed to absorb vibrational energy from the wheel/rail interaction, specific designs have not yet been developed.
. Increase damping in truck suspension	The reduction of groundborne vibration by the Wegman trucks used on the CTA 2400 Series vehicles has been partially attributed to extensive use of rubber bushings to eliminate metal-to-metal contacts. It has not been proven that this aspect of the design reduces ground vibration.
4. Flexible side frame	It has been conjectured that the better a truck is at equalizing loads between wheels, the lower the wheel/rail forces will be. Flexible side frames, such as those of the Wegman trucks used on the CTA (Chicago Transit Authority) 2400 Series vehicles are designed to help equalize the loads.
B. Wheel Treatments	
1. Resilient wheels	Resilient wheels have been found to reduce levels of ground vibration at frequencies above 30 to 40 Hz.
2. Aluminum-centered wheels	The reduced mass of aluminum-centered wheels reduces the unsprung mass and will result in some reduction of groundborne vibration.

Source: Track Support Systems

TREATMENTS	COMMENTS
A. Subway with Rigid Invert	
1. Increase structural mass	There is conflicting information regarding the degree to which structure mass reduces ground vibration, however, there is no question that the larger the structure mass, the lower the levels of ground vibrations.
2. Resilient fasteners	Resilient fasteners are used in virtually all new subways or other concrete track slabs. Changing from rigid fixation (e.g., wood ties embedded in concrete) to resilient fasteners significantly reduces ground vibration. Generally, the lower the vertical rail support modulus, the lower the levels of ground vibration. Hence, fasteners such as the "Cologne Egg" which have a low vertical stiffness, but maintain sufficient lateral and horizontal stiffness for stability requirements can be very effective.

TREATMENTS	COMMENTS
3. Lightweight floating slabs	Lightweight floating slabs such as those used at TTC, WMATA, and MARTA are very effective at controlling groundborne noise. They are very effective at reducing groundborne noise and vibration at frequencies above 20 Hz. If support pads are formulated correctly, maintenance costs are not increased. However, lightweight floating slabs add significantly to the cost of a subway, may require larger tunnel bores, and may increase noise inside cars slightly.
4. Heavyweight floating slabs	Where groundborne vibration at frequencies below 20 Hz must be controlled, a heavier than normal floating slab must be used. This may also be necessary to avoid interaction between the floating-slab resonance and the primary stiffness resonance of the trucks.
5. Resiliently supported ties	Resiliently supported ties (e.g., RS-STEDEF system) are often used in areas where noise reduction achieved with a floating slab is not required.
6. Use of heavier rail	This may achieve some reduction of groundborne noise and vibration, but the reduction is unlikely to justify the added cost.
B. Subway with Ballast-and-Tie Track	
1. Increase structural mass	See A, 1.
2. Ballast mats	Although rarely used in the U.S., ballast mats could reduce groundborne noise problems near existing ballast-and-tie subways. Ballast mats have been used in Europe and Japan to reduce ballast pulverization and improve electrical isolation.
3. Concrete ties	The added mass of concrete ties results in a slight reduction of groundborne noise and vibration.
4. Floating slabs	Since floating slabs are difficult to retrofit in existing tunnels and very few new U.S. subways use ballast, floating slabs will rarely be practical for ballasted subways in the U.S. An important exception is crossover areas which often use ballast.
5. Use of heavier rail	See A, 6.
6. Resilient fasteners	Attaching the rail to the ties with resilient fasteners has been suggested, however, this method is not effective at reducing low-frequency groundborne vibration.
C. At-Grade Ballast-and-Tie Track	
1. Trenches and underground barriers	Although trenches do not appear practical for subway applications, there are indications that they would be effective along at-grade trackways.
2. Ballast mats	Relatively little information is available on the effectiveness of ballast mats at reducing groundborne vibration from at-grade track. However, it is believed that ballast mats would be more effective when used in subways than when used on at-grade track.

TREATMENTS	COMMENTS
D. At-Grade Concrete Slab Track	
1. Trenches	See C, 1.
2. Resilient fasteners	See A, 2.
3. Resiliently supported ties	See A, 5.
4. Floating slabs	See A, 3 and A, 4. When using floating slabs at-grade, exposure to the weather must be considered. There are potential probems from water, dirt, and other contaminants short-circuiting the vibration isolation of the slab.
E. Aerial Structures	Groundborne vibration problems are relatively uncommon near aerial structures.
1. Trenches	See C, 1.
2. Resilient fasteners	Most new composite steel/concrete aerial structures use resilient fasteners to attach the rails to the concrete deck. These reduce the structure-radiated noise and the groundborne noise and vibration. Ground vibration can be reduced by retrofitting resilient fasteners to existing aerial structures.
3. Resiliently supported ties	See A, 5.
4. Floating slabs	See A, 3 and A, 4. It is very rare that such extreme measures would be required for an aerial structure, although a floating-slab aerial structure has been constructed in one instance for noise and vibration control.

APPENDIX B

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APPENDIX C
REPORT OF NEW TECHNOLOGY

This executive digest summarizes material contained in the Handbook of Urban Rail Noise and Vibration Control. The handbook is a unique guide focusing on the prediction and control of all types of urban rail transit noise. For the first time, information on acceptability criteria, noise measurement, and control of noise from vehicles, surface, aerial, and subway tracks, stations, ancillary equipment, and yards and shops is assimilated in one document. In presenting various information related to noise and vibration within the transit environment, this aggregation of recent research in this area will significantly enhance future efforts in predicting and controlling noise and vibration.

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