This report was prepared by the Technology Sharing Office of the U.S. Department of Transportation, which periodically issues documents on a variety of transportation topics. For a list of recent publications from the Technology Sharing Office, or for additional copies of this publication, please contact:

Office of Technology Sharing
U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center — Code 151
Kendall Square
Cambridge, MA 02142

(617) 494-2486

NOISE ABATEMENT

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the i exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufact herein solely because they are considered essential to the object of this report.

REPORT NO. UMTA-MA-06-0099-80-3

URBAN RAIL NOISE ABATEMENT

Program Digest

Reprint
July 1981

U.S. DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration

Contents

Overview 1
Scope of the Problem 1
Program Development 2
1 Noise Assessment 5
Assessment Methodology 5
Assessment Results 8
Comparison with APTA Guidelines 8
Cost-Effectiveness Studies 10
2 Technology Development and Evaluation 11
Wheel/Rail Noise 11
Development of Analytic Models for Wheel/Rail Noise 11
SEPTA Wheel/Rail In-Service Test Program 15
Results of In-Service Testing at SEPTA 17
Further Work on Wheel/Rail Noise Abatement Techniques 17
Elevated Structure Noise 19
Development of Analytic Models for Elevated Structure Noise 20
Further Research on Elevated Structure Noise 20
Elevated Structure Noise Abatement Treatments 20
Groundborne Noise from Subways 25
Development of Analytic Models for Groundborne Noise 25
Groundborne Noise Abatement Treatments 26
Propulsion System Noise 27
3 Technology Deployment 29
Glossary 32
Bibliography 34

Rail transit noise is a major environmental impact.

Overview

Scope of the Problem

Noise from urban rail operations is more than just annoying. Continued exposure to high noise levels produces human stress, fatigue, and possibly irreversible hearing loss. Recent census data combined with measurements of noise from elevated tracks indicate that in New York City alone, over half a million people are exposed to noise levels unacceptable by EPA standards.

Excessive noise lessens the attractiveness of urban rail transit as an alternative mode of transportation to the automobile. Negative public reaction to noise and vibration in neighborhoods surrounding transit lines may result in adverse economic impacts, such as reduced property values, and may result in public opposition to new transit lines.

Transit operators, transit patrons, and community residents have all expressed concern over transit noise and have indicated that noise reduction should be a priority. In New York City, public reaction led to the drafting of state legislation specifically aimed at regulating transit noise. A survey of transit properties conducted to determine the research requirements of the urban rail industry showed noise to be the most frequently cited area in need of federally funded research and development. (36)[1]

There are presently about 570 route miles of rail transit lines, and about 10,000 rapid transit cars in the United States. Planned expansions and new rapid transit systems will result in the construction of about 325 additional route miles of transit line and the purchase of more than 2,000 new cars by the end of this century. These developments offer an opportunity to apply engineering knowledge in acoustics and vibration to

[1]Numbers in parentheses refer to sources listed in the bibliography.

the design of track structures and cars. For those transit systems already in place, noise abatement techniques are needed that can be easily retrofitted on existing transit structures and equipment.

Program Development.

In response to these needs, the Urban Mass Transportation Administration (UMTA) established the Urban Rail Noise Abatement Program to assess the dimensions of the problem, to identify, develop, and test noise abatement techniques, and to share noise control technology with transit managers, suppliers, manufacturers, and others concerned with urban rail noise either professionally or as members of the general public.

The Urban Rail Noise Abatement Program provides a systematic approach to solving the urban transit noise problem. This approach has resulted in comprehensive scientific research and development projects, followed by extensive tests of applied technology. Program efforts have been explicitly designed to
needs of the transit properties
technologies which can be applie
by addressing problems comm
Through carefully structured
back and forth between transit o
ment manufacturers, and researc
opportunities for program revie
in order to ensure that the pr
adequate technical, operating,
data, and that implementable
usable products are developed

UMTA's Office of Rail an
Technology gives program g
Urban Rail Noise Abatement
three components of the progr
out under the technical directio
U.S. DOT Transportation Syst
Cambridge, Mass. These three p
nents are 1) assessment of th
noise problem, 2) development a
technology to control noise, an
tion of the results and deployme
technologies. Each of these ma

Urban rail noise and vibration affect passengers, operators, and persons living
communities.

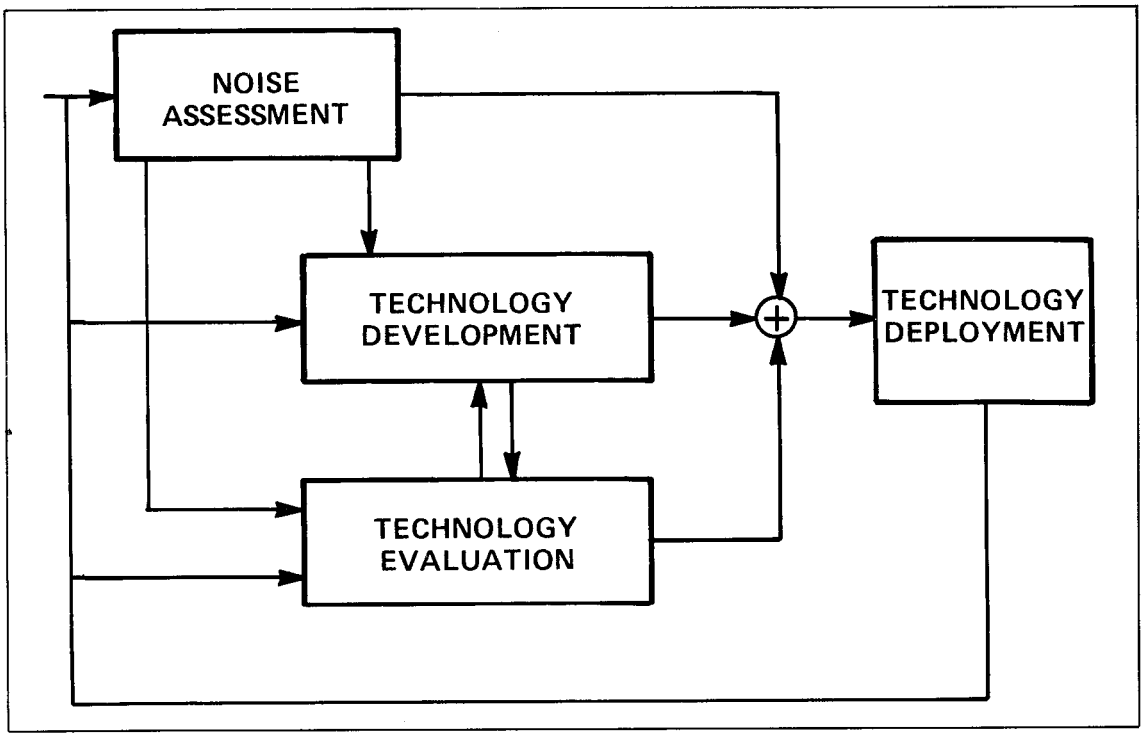


Figure 1. Relationships Among Urban Rail Noise Abatement Program Areas

has specific interrelationships with the others, and these relationships are indicated in Figure 1.

A discussion of the activities within the three major program areas forms the balance of this report. A brief description of these follows:

1. Noise Assessment

This section describes the effort to assess the extent and severity of the urban rail noise problem in the United States. When the program began, there was no comparable data on the magnitude of the noise problem in urban rail transit systems. A systematic survey was made in a standardized manner of the nine urban rail systems operating at the time, and noise levels on all these systems and their component parts were identified. The results were compared with the noise guidelines established by the American Public Transit Association (APTA), and the severity of the problem was determined. Noise abatement techniques in the current state-of-the-art were evaluated for both cost and effectiveness, and for each transit system estimates were made of the system-wide cost of reducing noise to specified levels. The results of the assessment program influenced the choices for further research, development, and evaluation, as well as the distribution of capital funds for noise abatement and control.

2. Technology Development and Evaluation

This section describes efforts to develop and evaluate improved noise control treatments. During the assessment phase, an effort was made to associate observed noise levels with specific sources and paths and to identify applicable noise abatement treatments. These

efforts were subsequently extended to develop remedies for the four types of urban rail noise which were isolated and which constitute the most severe problems. These are wheel/rail noise, elevated structure noise, groundborne noise, and propulsion system noise.

The mechanisms producing noise and the paths along which it is transmitted were investigated in great detail. It was necessary to conduct this basic research into the physics of urban rail noise so that a better understanding of the specifics of its generation and transmission could lead to the development of effective noise abatement methods.

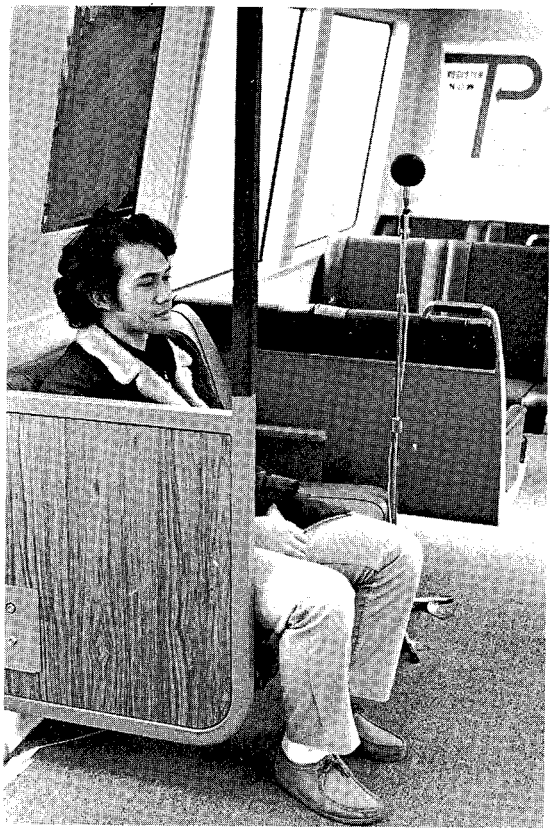
The actual cost and operating performance of noise abatement treatments are difficult to predict from experiments in the laboratory or on test tracks. In-service testing on transit systems is the only way accurately to gauge the performance of a given noise abatement procedure. Noise abatement technologies addressing the four noise categories have been and continue to be tested in transit systems
country.

3. Technology Depl

The ultimate success of the
in stimulating deployment of cos
control technology is depende
communication and informa
among all those involved in red
noise. The sharing of ideas an
data is essential to ensure that
opment, and evaluation are di
producing a technology which w
needs of transit operators and us
of the available technological re
ucts and an understanding of ho
be applied in the transit enviro
essential. This section outlines t
developed by the UMTA progr
deployment of technology.

1. Noise Assessment

Assessment studies of nine urban rail systems were conducted to determine prevailing noise levels and to estimate costs of noise reduction. The systems studied were the Massachusetts Bay Transportation Authority (MBTA) in Boston, the Southeastern Pennsylvania Transportation Authority (SEPTA) in Philadelphia, the Port Authority Transit Corporation (PATCO) running between Philadelphia and New Jersey, the Greater Cleveland Regional Transit Authority (RTA), the Bay Area Rapid Transit District (BART) in San Francisco, the Chicago Transit Authority (CTA) and the New York City Transit Authority (NYCTA) along with the Staten Island Rapid Transit Operating Authority (SIRTOA), and the Port Authority Trans-Hudson (PATH) system operating between New York City and New Jersey. These were the U.S. rapid transit systems operating at the time. The Washington, D.C. and Atlanta systems had not yet begun operations.



Noise levels are measured inside moving transit cars as part of UMTA's assessment studies.

Assessment Methodology

As part of the assessment studies, a standard methodology was developed for measuring noise levels and for estimating the costs of noise reduction. This methodology was developed in conjunction with a pilot assessment study done on Boston's MBTA, (12) and then used in the subsequent assessments. (13-18)

Standard technical measurement procedures are important to ensure accurate measurement of noise levels. Such procedures include the type of recording equipment to be used, placement of microphones, and recording conditions. Assessment teams responsible for measuring noise on the other systems visited the MBTA. Working independently, they used the techniques developed in the pilot study to make simultaneous measurements of MBTA noise levels. The close agreement among their findings validated the measurement procedures, and ensured the compatibility of the noise measurement results for all the systems.

The measure of sound used in the assessments was the A-weighted decibel, or dBA. This measure weights the various frequencies comprising a sound in a manner which closely approximates the perceptions of the human ear. To provide the reader with a sense of the A-weighted decibel scale, Figure 2 presents transit noise levels in dBA along with noise levels of other sources affecting the typical community. The basic indicator of noise level used during the assessments was L_A (MAX), the maximum A-weighted noise level occurring over a period of time.

In the assessment methodology, noise was categorized by source (where the noise origi-

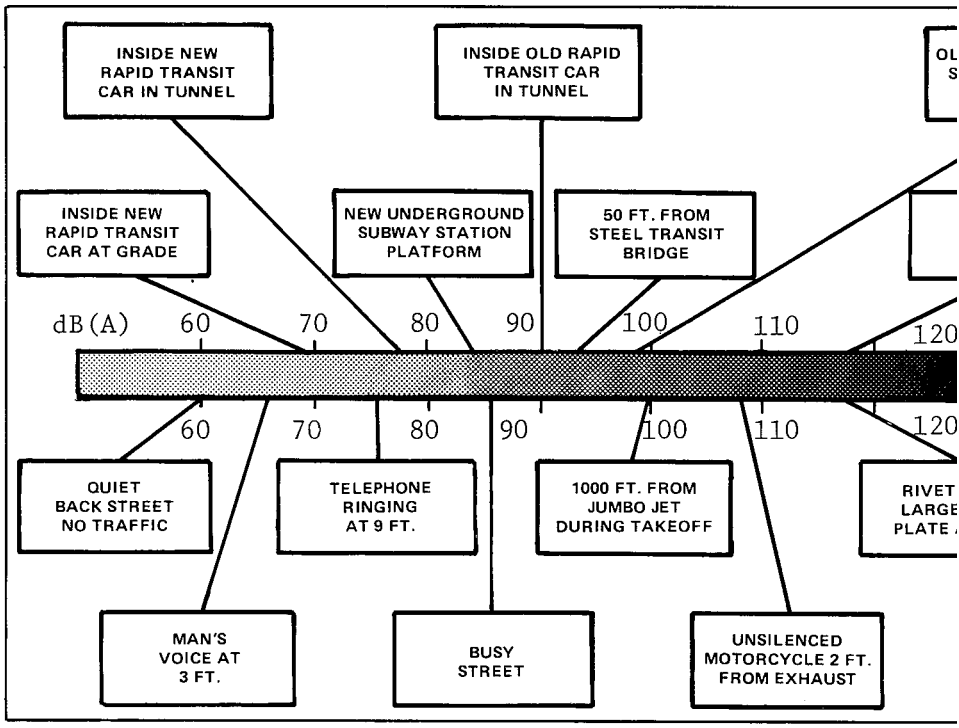


Figure 2. Typical Noise Levels in dBA

nated from), path (how the noise was transmitted), and receiver (where the person hearing the noise was located). The primary categorization was in terms of the receiver. *In-car noise* is heard by persons who are riding in transit cars; *in-station noise* is heard by persons waiting in stations; and *wayside noise* affects persons living or working in areas adjacent to transit lines. The noise in each of the above categories may originate from one or more sources and travels away from the source along various paths. Figures 3, 4, and 5 illustrate the paths noise follows in each of the noise categories.

For assessment purposes, transit systems were divided into segments acco system characteristics, such a vehicle type, trackbed type, a location. Measurement of nois points along the system was no selection of measurement locat ing typical combinations of syst tics allowed the extrapolation of levels to the entire system. In ad ing general noise levels, noise an squeal noise on curves, air brak and mechanical door operation tematically measured.

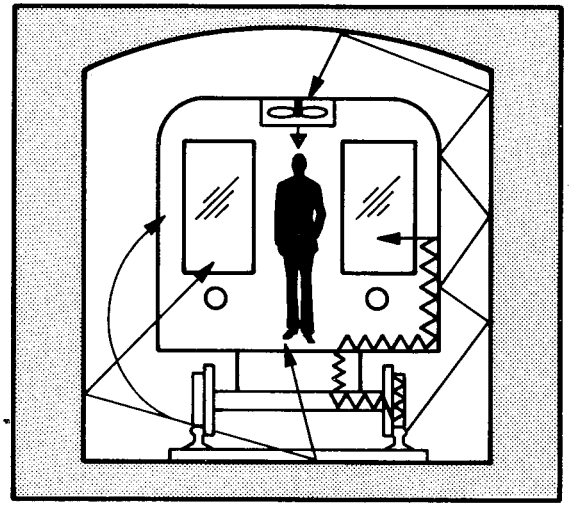


Figure 3. In-Car Noise Sources and Paths

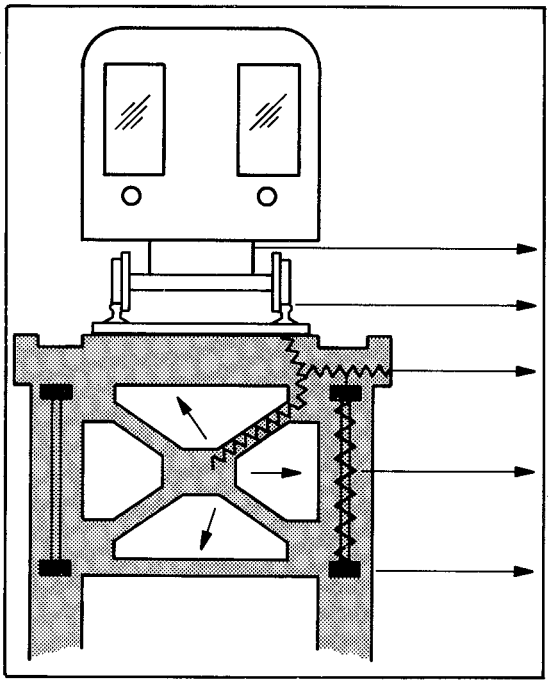


Figure 5. Wayside Noise Sources and Paths

PATHS:

AIRBORNE

STRUCTURE-BORNE VIBRATION

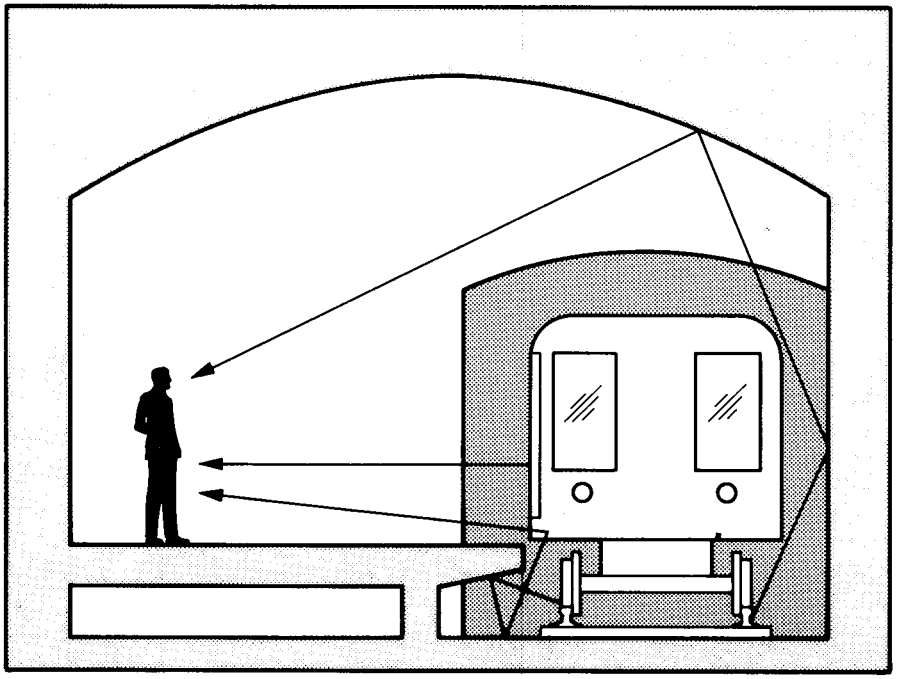


Figure 4. In-Station Noise Sources and Paths

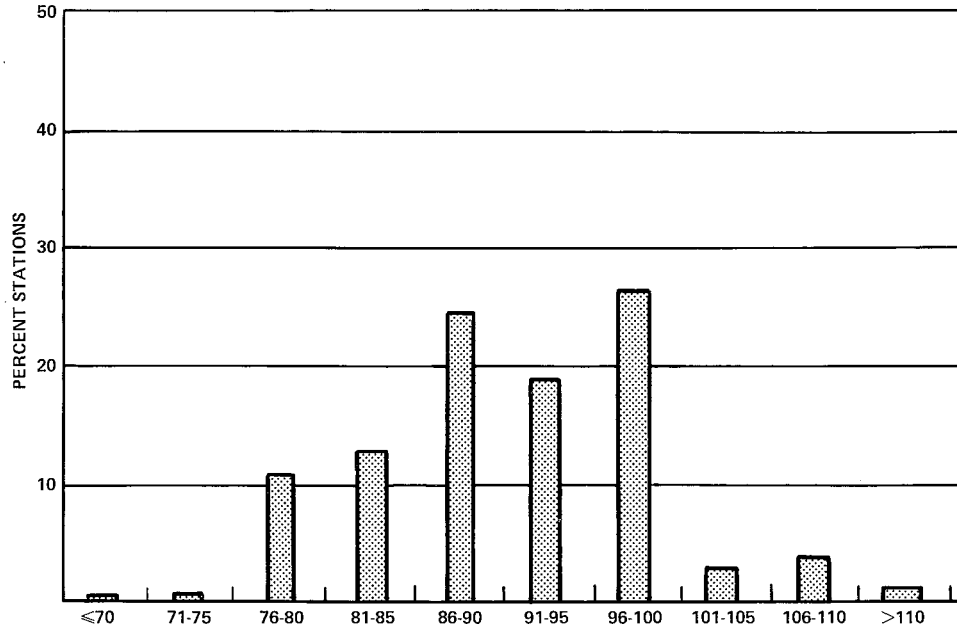


Figure 6. Maximum Noise Levels in Transit Stations Nationwide (in dBA)

Assessment Results

Results of the individual system assessments (12-18) were summarized into a national assessment report. (10) Data on noise levels was aggregated for in-car, in-station, and wayside noise. Figure 6 shows the aggregate distribution for in-station noise.

Certain system characteristics were found to be associated with higher noise levels. The location of track, i.e., underground, at grade, or elevated, was a principal determinant of noise level. Underground track typically produced higher in-car and in-station noise levels than aboveground track. Wayside noise levels associated with elevated track were typically higher than those associated with at grade track. Other conditions correlated with high noise levels included high train speed, jointed as opposed to continuous welded rail, flat spots on wheels, rough rail surfaces, and sharp curves in the track.

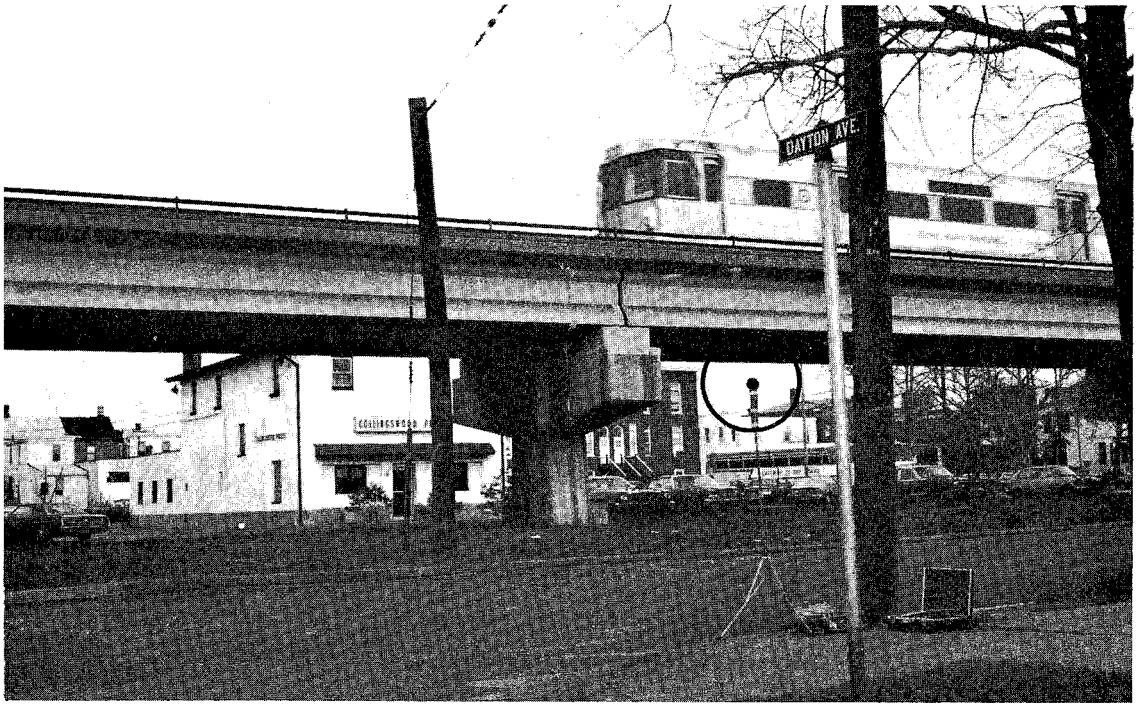
The age of the transit system was another determinant of noise levels. In-car noise levels were typically higher in older c
ground sections of track, a cond
on SEPTA, NYCTA, and CTA.
with acoustically treated cars an
erally had lower in-car and in-stati
Underground stations on the
which had been acoustically trea
noise levels than aboveground l
despite the fact that in general un
tions are noisier than abovegr
Wayside noise levels showed
between old and new systems a
influenced by factors such as tr
wheel/rail condition.

Comparison with AP Guidelines

As part of the national asse
maximum noise levels on each of
systems were compared with t
guidelines established by the Ar
Transit Association (APTA). Th

Microphones placed in stations measure sounds of arriving and departing trains as part of the assessment program.

Noise levels of moving trains are measured at specified distances from the track on each of the nine transit systems studied.



represent the transit industry's own view of what is desirable and practicable in the control of rail transit noise. The guidelines are designed to insure that private conversations can be carried on in normal voices. At background noise levels of 78 dBA, people who are one foot apart can communicate in normal voices, but at 83 dBA, they must raise their voices in order to be heard.

The APTA guidelines specify acceptable maximum in-car noise levels from 70 to 80 dBA and in-station noise levels from 75 to 85 dBA, varying according to track structure type. For underground track, noise level goals were set higher because it is not practicable to reduce noise levels to the same degree as for above-ground track. Wayside noise level goals vary in relation to the type of buildings and land use in the wayside community. These goals range from 70 dBA for residential areas to 85 dBA for industrial areas.

In most cases, the noise levels reported in the national assessment exceeded those cited in the APTA guidelines. In-car noise levels were above those cited in the APTA guidelines for approximately 90 percent of the total route mileage covered. In-station noise levels exceeded APTA guidelines for approxmately 95 percent of the total route mileage covered.

Cost-Effectiveness Studies

Following completion of the eight assessments, studies on the cost and effectiveness of various noise abatement treatments were done on the same transit systems. (13, 23, 34) The methodology developed to estimate costs of noise reduction for the MBTA served as a model for the other systems. Estimates were made of the effectiveness of known abatement treatments and the cost of applying treatments to specific sources and paths. This information was incorporated into a computer program which calculated the minimum cost to reduce noise to various specific dBA levels, for example to 70 dBA, 80 dBA, or 90 dBA. Cost estimates were done for in-car, in-station, and wayside noise. Included in the estimates was the cost of elimi-

nating noise anomalies such as
well as the reduction of genera

These studies, along with a
cost-effectiveness on the NYC
sis for on-going work on r
cost-effectiveness. (12) Under
deployment program area, a co
package is being developed k
(Computerized Procedure for
Abatement Cost-Effectiveness
will serve as a tool for transit m
ers involved in noise control p
them to select that combinatio
ment techniques which will red
levels most cost-effectively or t
native noise control strategies

2. Technology Development and Evaluation

Four types of urban rail noise constitute the most severe problems: wheel/rail noise, elevated structure noise, groundborne noise, and propulsion system noise. In this chapter technology development and evaluation activities are described for each of these categories of noise.

Wheel/Rail Noise

The sounds made by the interaction of steel wheels on steel rails is a major contributor to the urban rail transit noise problem. A major research effort has been undertaken by UMTA to develop a better understanding of the mechanisms involved in wheel/rail noise production. The effort involves the development of analytic models to predict wheel/rail noise, the testing of model predictions against laboratory and field measurements, and the use of these findings to improve the effectiveness of wheel/rail noise abatement treatments. (31, 32, 33)

Development of Analytic Models for Wheel/Rail Noise

Wheel/rail noise falls into three broad categories, each produced by a different mechanism: squeal, impact, and roar. Squeal (or screech) is the high-pitched noise produced as a train rounds a sharp curve. Impact noise is the "clickety-clack" or banging sound heard as the train travels along the track. Roar is a steady sound produced continually by wheel/rail interaction.

All wheel/rail noise is generated by the interaction of wheel and rail. This interaction produces a force at the point where the wheel and rail meet which causes both to be set into vibratory motion, and, in turn, to radiate sound waves outward. Figure 7 is a schematic representation of the noise generation process for wheel/rail noise.

The first analytic models developed by UMTA were for the processes of vibratory response and sound radiation of the wheel and rail since these processes are fundamental to

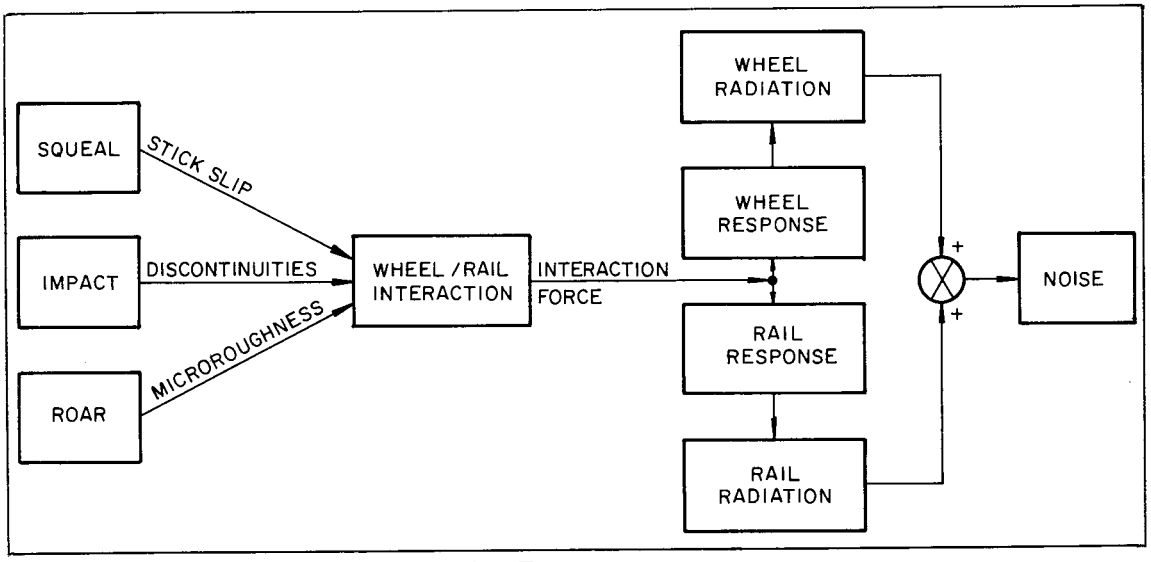


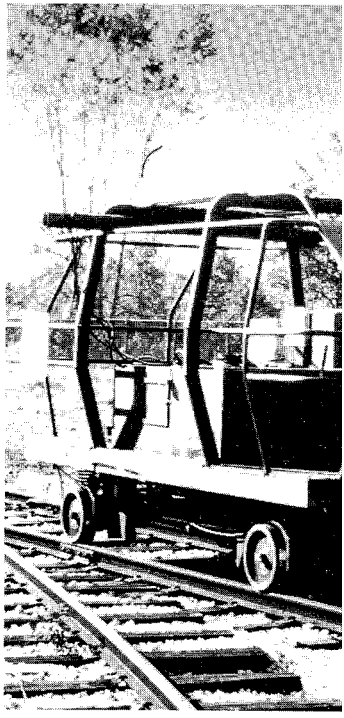
Figure 7. Wheel/Rail Noise Generation Process

wheel/rail noise generation. The models were tested in a series of laboratory experiments which employed an electromagnetic shaker to simulate wheel/rail interactions.

Following this, analytic models were developed for the mechanisms producing squeal, impact, and roar noise. These models were verified through both laboratory and field tests. A 1:8 scale model of a transit car undercarriage was used in the laboratory testing. The field tests employed a small 4-to-6 passenger personal rapid transit (PRT) vehicle with steel wheels running on steel track.

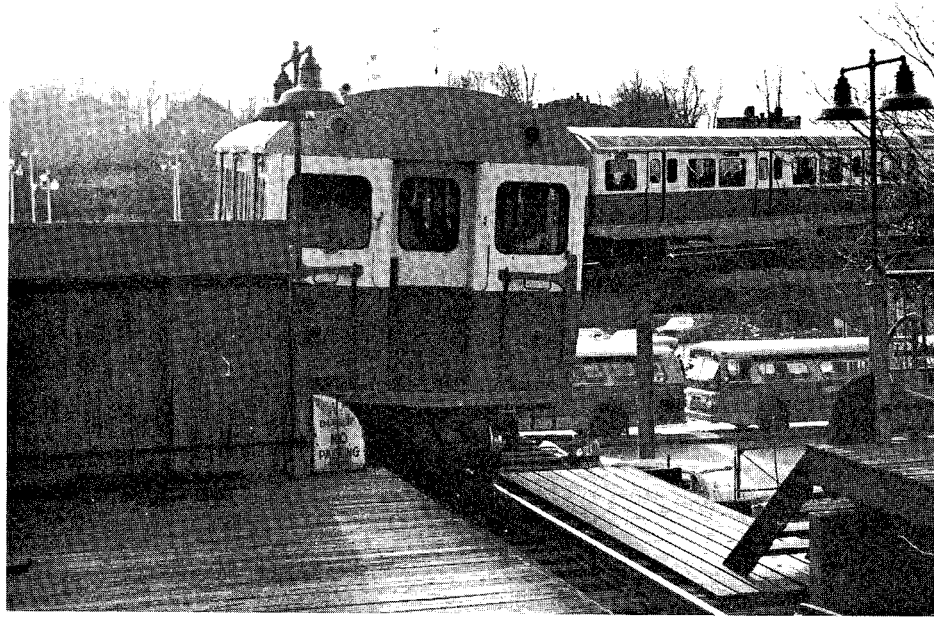
The test results in combination with existing knowledge produced a better understanding of the mechanisms involved in the production of squeal, impact, and roar noise.

Squeal noise appears to be produced in the following manner. A typical transit car is supported on two 2-axle trucks. The axles are rigidly attached to the truck making it difficult for the wheels to conform to the geometry of the rail on sharp curves. When rounding curves, the wheels do not roll continuously along the rail, but must slide laterally a certain amount. The



Experiments performed with were used to verify wheel/rai

Train squeals rounding sharp curve on elevated section of track.



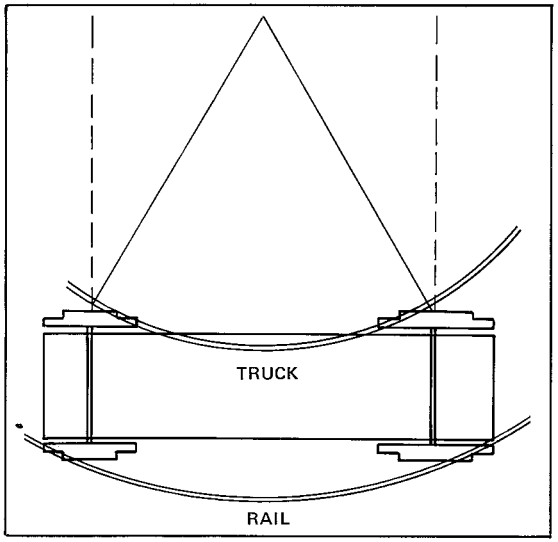


Figure 8. Squeal Noise Generation

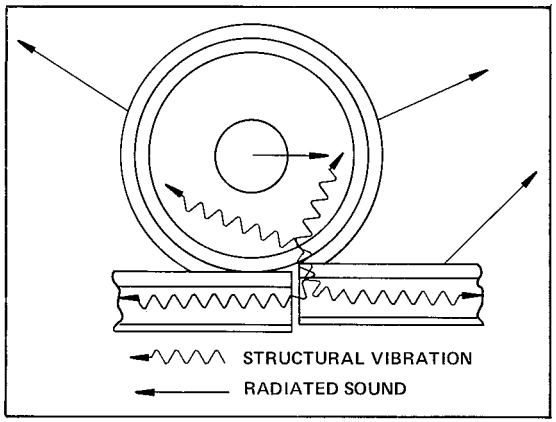


Figure 9. Impact Noise Generation

result is an alternate sticking and slipping motion along the rail known as "crabbing." This imperfect orientation of the wheels to the rail, illustrated in Figure 8, allows the "stick-slip" motion to begin. It is this "stick-slip" coupled with the vibratory response of the wheel that produces a high pitched squeal. The most prominent factors influencing squeal noise are the ratio of the radius of the curve to the length of the truck wheelbase, the vibration damping characteristics of the wheels, and the degree of adhesion between wheel and rail surfaces.

Impact noise is produced by discontinuities in the surfaces of the wheel or the rail. These discontinuities consist primarily of uneven rail joints and of worn areas on the rim of the wheel known as "wheel flats." Wheel flats are produced by locking of wheels during braking. Findings indicate that if both rail ends are at the same height, impact noise is negligible. If the first rail end (i.e. the rail on which the train is approaching) is higher than the second rail end ("step-down joint"), the noise level increases with speed up to a point beyond which it remains constant. When the first rail end is lower than the second rail end ("step-up joint") as illustrated in Figure 9, then the noise level increases constantly with train speed. Thus step-up joints represent a more serious noise problem. Noise due to wheel flats behaves in a manner similar to step-down joint noise — above a certain speed noise levels do not increase.

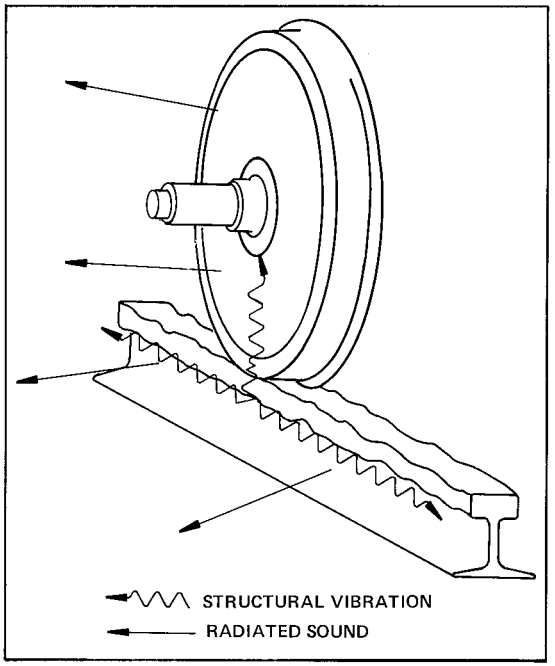


Figure 10. Roar Noise Generation

Roar noise is due to small-scale roughness on the surface of wheels and rails as illustrated in Figure 10. According to research results, the larger the contact patch (area in which the wheel and rail are in contact), the less roar noise is generated. Another finding indicates that at frequencies where roar noise peaks, the rail

predominates over the wheel as the radiator of noise.

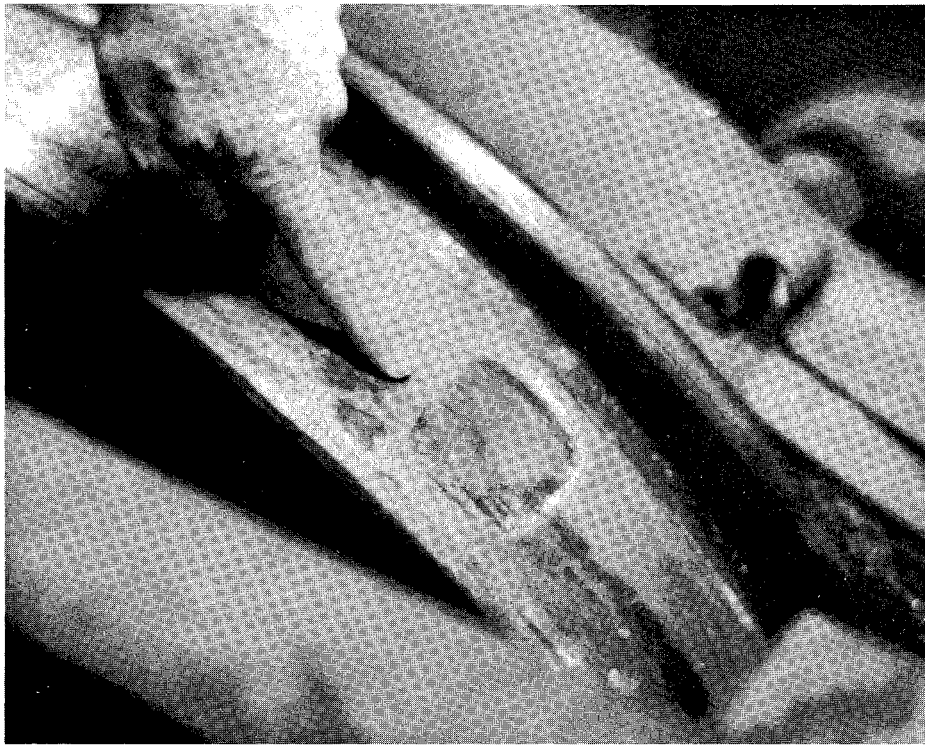
Based on the increased understanding of wheel/rail noise-generating mechanisms obtained through model development and validation, the following ways to abate wheel/rail noise suggested themselves. Although valid in theory, not all of these methods are equally practical for application on transit systems.

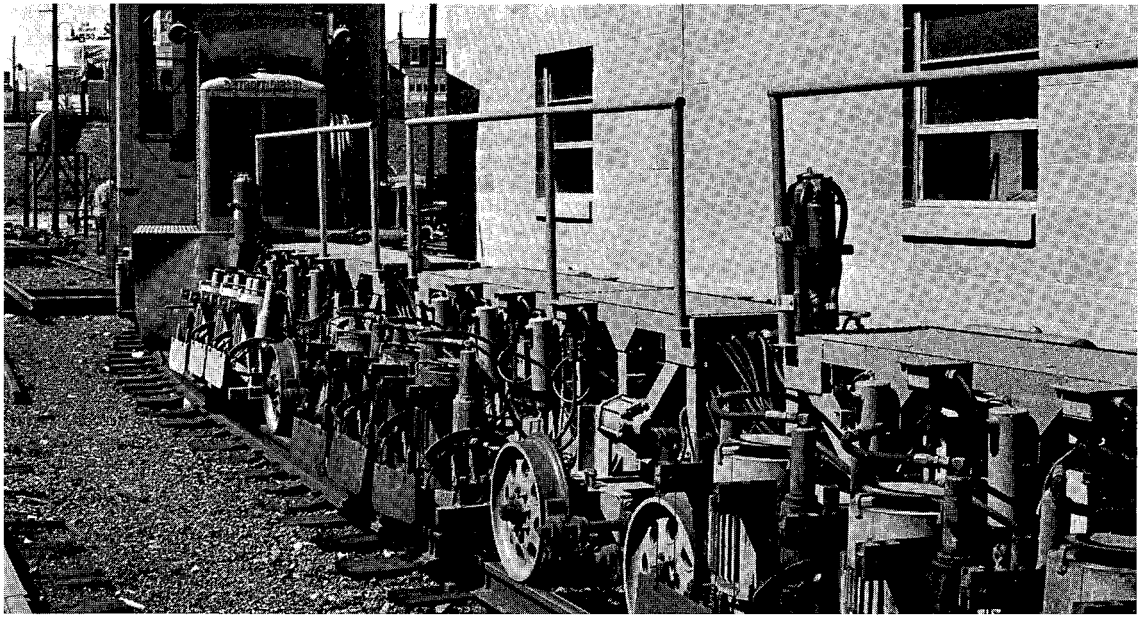
Squeal noise may be reduced by preventing the stick-slip mechanism or by lessening the vibrations produced by it. Trucks with shorter wheelbases or articulated trucks (i.e. trucks which pivot in the center allowing axles to conform to curves) may prevent crabbing and hence stick-slip. Lubrication of the wheel and rail can prevent the stick-slip mechanism from being activated. Finally various damping devices applied to the wheel can reduce squeal by suppressing the vibrations created by the stick-slip mechanism.

Impact noise generated b
ties may be eliminated by the
(elimination of rail joints) or
maintenance to keep rail join
ment. The contouring of the se
also help reduce impact at
noise due to wheel flats can be
tine inspection of wheels and
(machining) of damaged whee
ient wheels (i.e. wheels with
between the tread and hub) n
noise by lessening vibrations
the wheel from the point of i

Roar noise can be reduce
grinding of rails (machining of
truing of wheels. Other techni
iently treaded wheels (i.e. whe
resilient material on the tread o
layer of steel) could possibly
by creating a larger contact p
wheel and rail, but need furth

Wheel flats are one cause of impact noise.





SPENO grinding train removes rail roughness by lowering abrasive wheels onto the rail surface.

SEPTA Wheel/Rail In-Service Test Program

In order to evaluate the acoustical effectiveness, durability, and costs of various wheel/rail noise control techniques, UMTA undertook an in-service testing project on the SEPTA system (4-8). Included in the testing were (1) resilient wheels (wheels manufactured with a resilient material between the tire and hub that acts to damp vibration), (2) damped wheels (standard wheels retrofitted with a damping device to reduce vibrations), (3) wheel truing (machining wheel tire surfaces to remove irregularities created during train operations), (4) rail grinding (grinding of rail running surfaces to remove roughness created by train operations), and (5) the use of welded rails (welding rail ends together in order to eliminate the impact which occurs at rail joints) were evaluated as a noise control treatment.

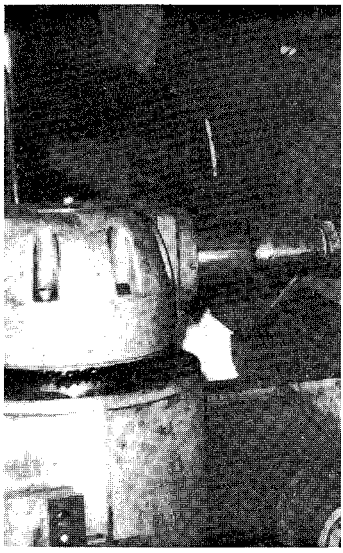
During the in-service testing noise and vibration measurements were made for a number of different combinations of train speeds, track structures, and rail types. Wheel truing and rail grinding were evaluated by comparing the performance of factory new wheels, recently-trued wheels, and worn wheels, and of recently-ground rail and worn rail. Following the first round of testing, wheels and rails were allowed to wear naturally during a year of in-service operations to determine how well they held up over time. After the year of wear, the various noise abatement techniques were retested.

Three types of resilient wheels were tested — the Acousta Flex wheel, the Penn Cushion (Bochum) wheel, and the SAB wheel. These wheels are illustrated in Figure 11. During the course of the testing, each type of resilient wheel developed some form of operational difficulty and had to be withdrawn from the study. The SAB and Bochum wheels sustained damage due to overheating caused by the application at high speeds of the tread braking system, used on SEPTA as a backup to the regular dynamic braking system. These problems raise questions about the compatibility of resilient wheels with tread braking systems although the two have been used together successfully on other transit systems. On the Acousta Flex wheel, a bonding

failure occurred between the resilient material and the rim caused by incomplete bonding during manufacture.

The damped wheels initially scheduled for testing were considered unsatisfactory and were not included. In their place, "ring-damped" wheels were tested. These are standard wheels with a groove cut on the inside of the tread and a metal ring snapped into the groove. The ring, although restrained by the groove, is free to move within it and acts to damp vibration.

In addition to the acoustic measurements, vibration levels were measured to determine if the wheel/rail noise abatement techniques were also effective in reducing vibration. Measurements were taken along welded track test sections in the subway and on elevated structure, for trains with worn and trued wheels and for trains with each of the three types of resilient wheels. Tests were performed both before and



An underfloor milling machin truing operations on SEPTA.

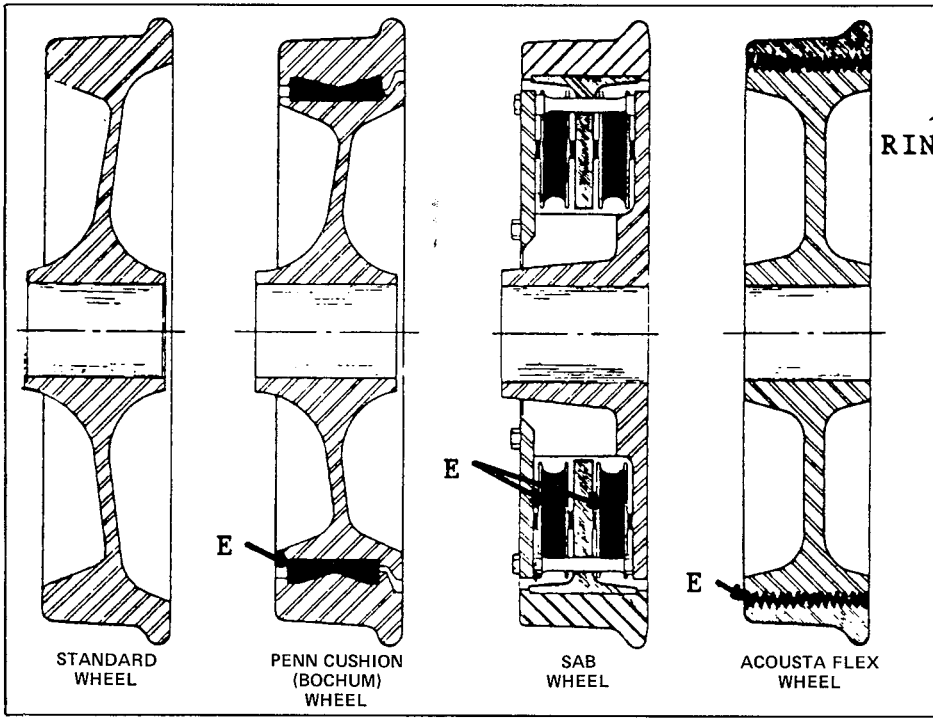


Figure 11. Standard, Resilient, and Ring-Damped Wheels Tested at SEPT the Location of Elastomeric Material on the Resilient Wheels).

after rail grinding. (A discussion of groundborne and structureborne vibration is contained in upcoming sections of this document.)

Measurements were also taken of the noise generated by the train's propulsion system. If noise from this source is high enough, it can mask reductions in wheel/rail noise produced by the abatement treatments. To gauge the importance of propulsion system noise on SEPTA, a transit car was raised above the track, and noise measurements were taken with the propulsion system running. (A discussion of propulsion system noise is contained in an upcoming section.)

Results of In-Service Testing at SEPTA

Some significant reductions in wheel/rail noise were observed during the SEPTA in-service testing. Resilient wheels and ring-damped wheels were found to produce large reductions in wheel squeal noise on curved sections of track. In certain cases, squeal noise was eliminated completely. Typical reductions were on the order of 10 dBA, but the perceived decrease in noise was even greater due to the annoying character of squeal noise.

Welded rail was found to be a significant improvement over jointed rail with an average noise reduction of 4 dBA in the wayside community. Again the subjective impression of reduction was greater than indicated by the dBA reduction because of the annoying character of impact noise.

Except for the above-mentioned findings, noise reductions achieved were not dramatic and typically were not enough to make a noticeable difference in transit cars or in the surrounding community. Although effective on curved track, resilient wheels and ring-damped wheels did not produce noteworthy reductions on tangent (straight) track. Also, since wheel flats and rail corrugations were not noticeably present on the SEPTA system, wheel truing and rail grinding were not particularly effective. Another factor was the level of propulsion system noise. In general propulsion system noise was comparable in magnitude to wheel/rail noise on the SEPTA system, and thus limited the reduction in wheel/rail noise that could be observed. In order to produce dramatic reductions in noise levels on SEPTA, both propulsion system noise and wheel/rail noise must be abated simultaneously.

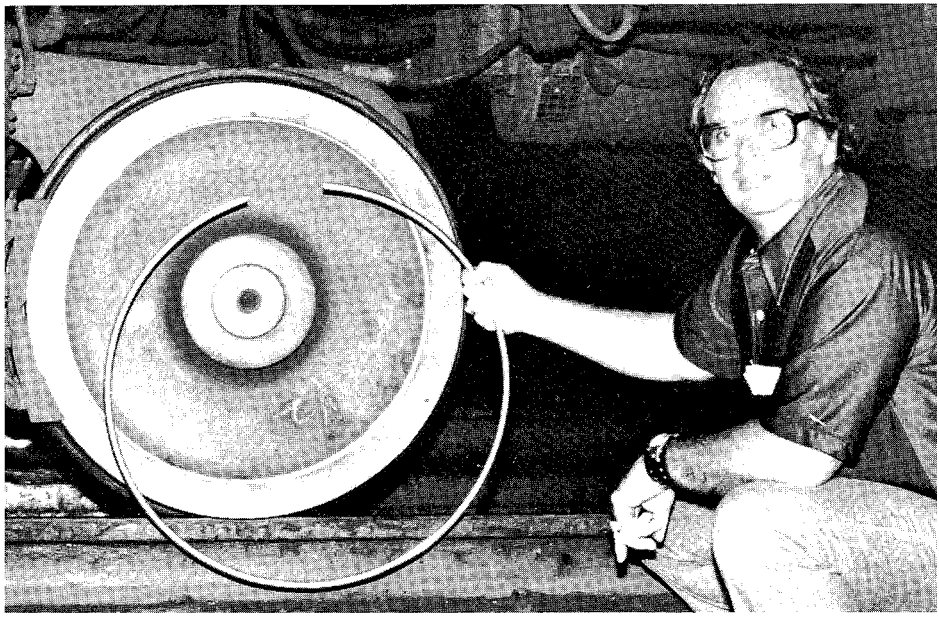
Vibration levels measured on SEPTA were found to be significantly reduced by the use of resilient wheels. Wheel truing and rail grinding did not produce significant vibration reductions on SEPTA although data from other systems suggests that these techniques are effective when noticeable wheel flats and rail corrugation are present on a system.

As mentioned above, resilient wheels tested developed problems during operation and may not be compatible with the use of tread braking. The ring-damped wheels also developed operational difficulties during the course of the study. Over a 10-month period, the rings "froze" in the grooves eliminating any abatement effectiveness. This situation has not arisen with ring-damped wheels in use on other systems, for example in Chicago and in London where they have been used without problems. It appears that corrosion or accumulated brake dust may be responsible for the adherence of the rings in the grooves. Further investigation of the problem is called for.

Further Work on Wheel/Rail Noise Abatement Techniques

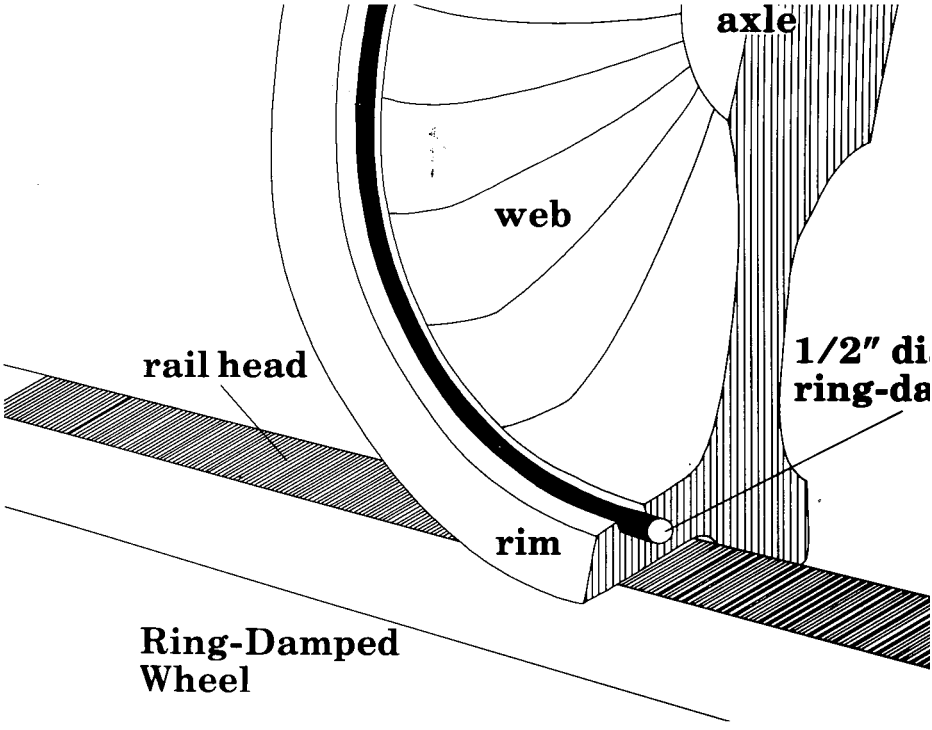
Work on improving the effectiveness of wheel/rail noise abatement treatments is being continued. Previously developed mathematical models of wheel/rail interaction will be refined based on the collection of new data and on field tests. The testing will be performed at the Pullman Standard test track in Champ Ferry, Indiana and at the Department of Transportation's Transportation Test Track in Pueblo, Colorado, and at several transit systems, including NYCTA, MBTA, and CTA.

For selected wheel/rail noise abatement treatments, the improved models will be used to optimize the design parameters of the treatments, i.e. the models will be used to predict which design changes will produce maximum



Vibration-damping rings are placed in grooves cut in the rim of the wheel.

Rings snapped into grooves on wheels reduce squeal noise by damping wheel vi



Noise levels for trains operated on elevated structures can be as much as 20 dBA higher than for trains operated at grade.

reductions in noise levels. Once designs have been optimized in this way, actual hardware will be obtained or manufactured, and will undergo field testing. The most successful treatments will then be selected for in-service testing on transit systems.

Elevated Structure Noise

When a train travels over an elevated structure, vibrations created by wheel/rail interaction are transmitted through the track to the supporting structure. The vibrating structure radiates noise to surrounding areas, increasing noise levels significantly over those produced by trains running on at grade track. Elevated structure noise levels can be as much as 20 dBA higher than those for at grade train operations.

Noise from elevated structures is a significant problem on U.S. transit systems; 30 percent of all urban transit route mileage is on elevated structures. Along much of this distance, the wayside community is within 50 feet of the track and experiences noise levels in excess of 90 dBA. In New York City alone, there are 70 route miles of elevated structure. Current technology does not appear adequate for reducing the noise levels near elevated structures on the New York City system to 85 dBA. More effective ways of reducing noise in communities near elevated transit lines are needed.

Development of Analytic Models for Elevated Structure Noise

During the initial stages of the program, a review was conducted of existing knowledge on the prediction and control of urban rail noise and vibration. (24) The focus of the review was on the paths along which noise and vibration propagate as they travel outward from the source rather than on the generation of noise at the source. Two areas treated in the review were selected for further study, elevated structure noise and vibration and groundborne noise and vibration from tunnels.

With regard to elevated structure noise and vibration, the review found prediction techniques inadequate. Correlations existed between noise levels and general types of elevated structures; for example steel elevated structures were typically noisier than concrete elevated structures. However, it was not possible to predict the noise radiated by individual structural elements. This more detailed knowledge was needed in order to estimate noise levels produced by new elevated structure designs and by design modifications made on existing structures for noise abatement purposes.

To this end, mathematical models of elevated structure noise have been developed. (21) Three different types of elevated structures were modeled, including concrete deck on steel plate girders, open tie deck on steel plate girders, and open tie deck on open web steel girders. These models were tested against field measurements on Boston's MBTA for the three types of elevated structures. The test results partially validated the accuracy of the models.

One of the significant findings of this research was that rails are the dominant noise source at high frequencies, while steel girders dominate the mid-range frequencies. In order to significantly reduce the noise levels, noise from both rails and girders must be reduced.

Further Research on Elevated Structure Noise

A new research effort on elevated structure noise is underway. Tasks include the review of noise rating criteria to select t
for elevated structure noise, ar
vated structures, development
mathematical models, and
design guidelines for elevated
control.

The review of noise ra
already been accomplished. (2
selected was L_{dn}, which repres
A-weighted sound level over
weighting applied for nighttime
ally, a method was developed t
ment of noise impact over an e
The Fractional Impact Meth
this by weighting sound levels
exposed and summing impac
subareas.

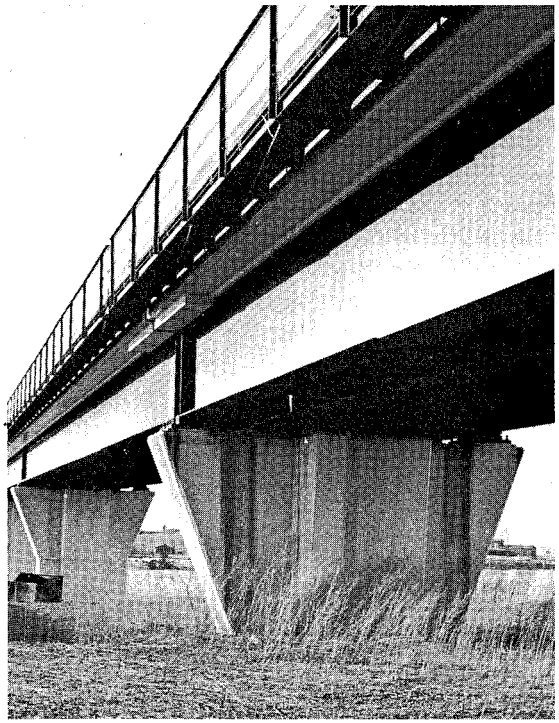
Present and planned U.S
tures have been inventoried to
types of structures, their length
tics of these structures that
directly to noise generation, ty
associated with these struc
number of people impacted by

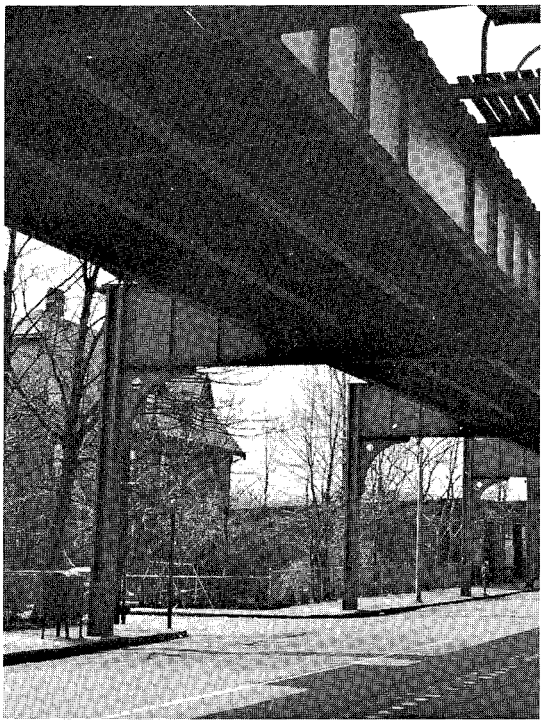
The models of elevated str
vibration previously develope
proved through extension and
example, the model of wheel/ra
be incorporated into the el
model to improve prediction c

Using the improved analy
data from European, Japan
States studies of elevated stru
noise control treatments, estim
of the amount of noise re
through the use of different
information will be summarize
lines for each type of elevate
presented in a form understanc
cialist. Potential sites will be sel
United States that would be
for trial application of elevate
control treatments.

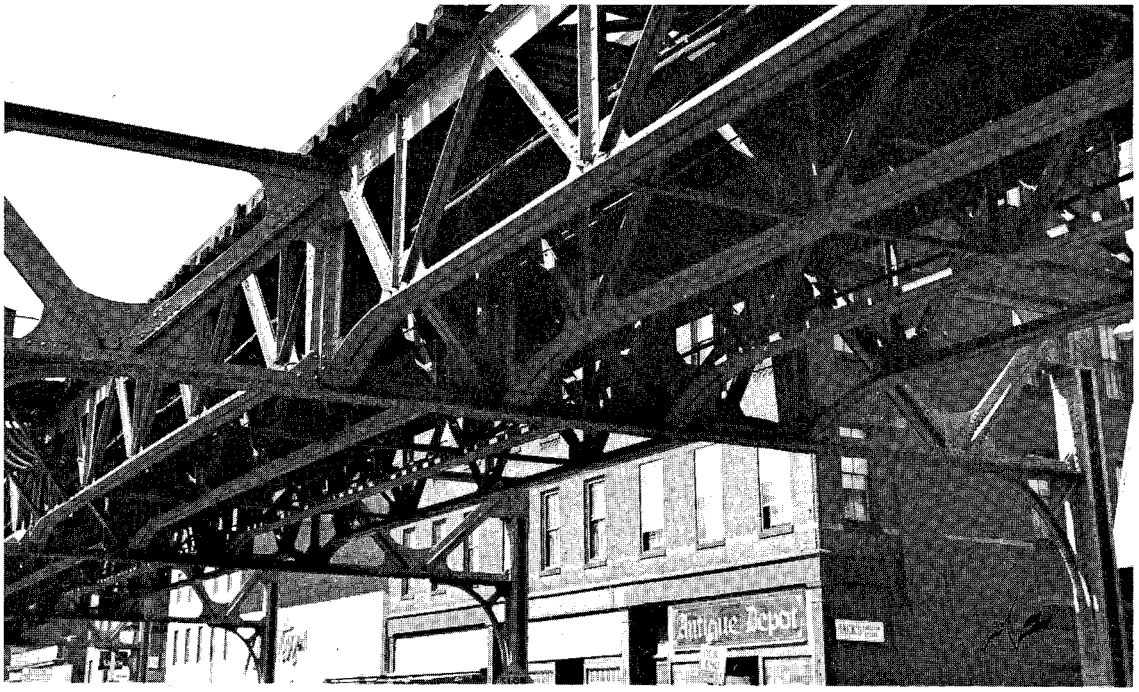
Elevated Structure No
Abatement Treatments

Based on research condu
following noise abatement tech





UMTA-sponsored research developed computer models to predict noise on three types of elevated structures — concrete deck on steel plate girder (left), open tie deck on steel plate girder (right), and open tie deck on open web girder (bottom).



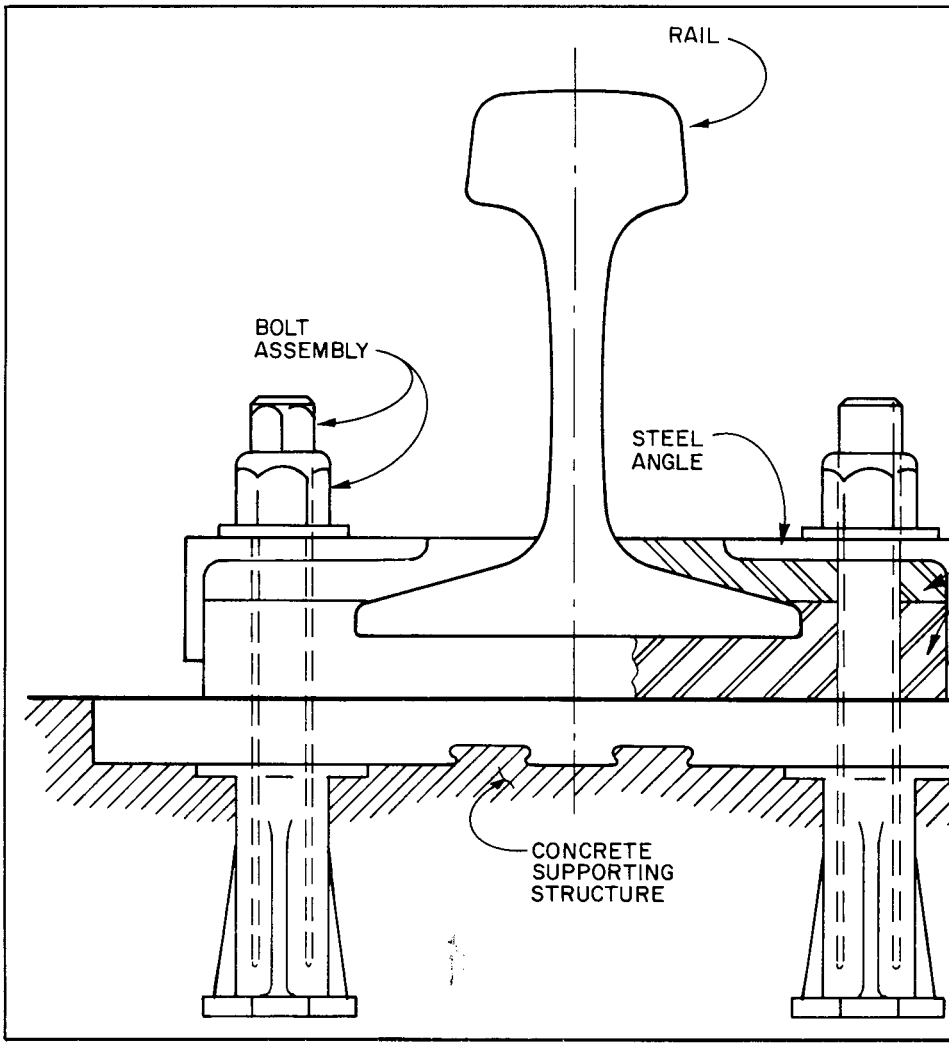


Figure 12. One type of resilient rail fastener

have the most promise for reducing elevated structure noise levels.

Since elevated structure noise is produced in part by the transmission of vibration to the structure, techniques which reduce rail vibration also reduce elevated structure vibration and noise. Rail grinding, wheel truing, and the use of welded rail instead of jointed rail all fall in this category. Rail grinding and welding may present safety and structural problems, however, which must be resolved.

Another strategy is to limi
vibration that is transmitted t
Resilient rail fasteners, which c
resilient material placed betwee
roadbed, reduce the transmiss
One type of resilient rail fastener
in Figure 12. The use of ballast, v
placing crushed rock between
roadbed, acts to absorb vibratio
transmission to the elevated
added weight, however, can c

problems on older elevated structures. Moreover, most types of elevated structures are open deck and would have to be redesigned to carry ballast.

Shielding the elevated structure to prevent the radiation of noise into the wayside community is another abatement strategy. Barriers along the side of the tracks can reduce noise from the rails and enclosure of the sides and undersides of an elevated structure can block noise radiated from structural elements. Barriers and enclosures, however, may be prohibitively expensive.

While further analytical research on elevated structures is proceeding, various in-service tests of elevated structure noise control treatments are being carried out. One example is the recent test of resilient rail fasteners performed on elevated structures in New York City by the NYCTA. Butyl rubber pads were inserted between the rail and the wood ties. Noise measurements made before and after installation of the rubber pads revealed a varying reduction in the wayside noise from the track, depending on train speed. Figure 13 shows noise levels before and after installation of the resilient rail fastener treatment. The lack of noise reduction above 30 mph is believed to be because the propulsion system noise becomes dominant at higher speeds. Although this in-service testing was not a formal part of the Urban Rail Noise Abatement Program, the Transportation Systems Center did provide technical assistance for measurements and analysis.

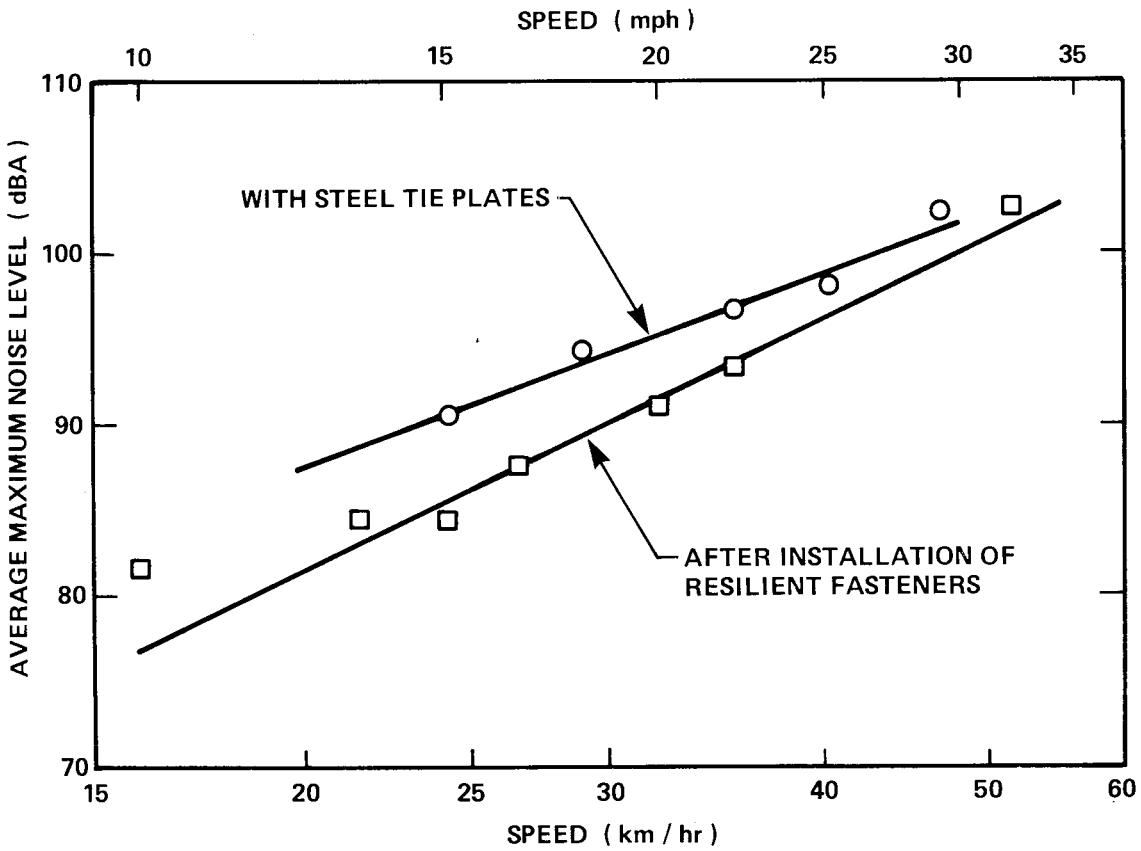


Figure 13. Effect of Resilient Fasteners on Wayside Noise at 25 feet from NYCTA Elevated Structure

Train operations cause surrounding buildings to vibrate.

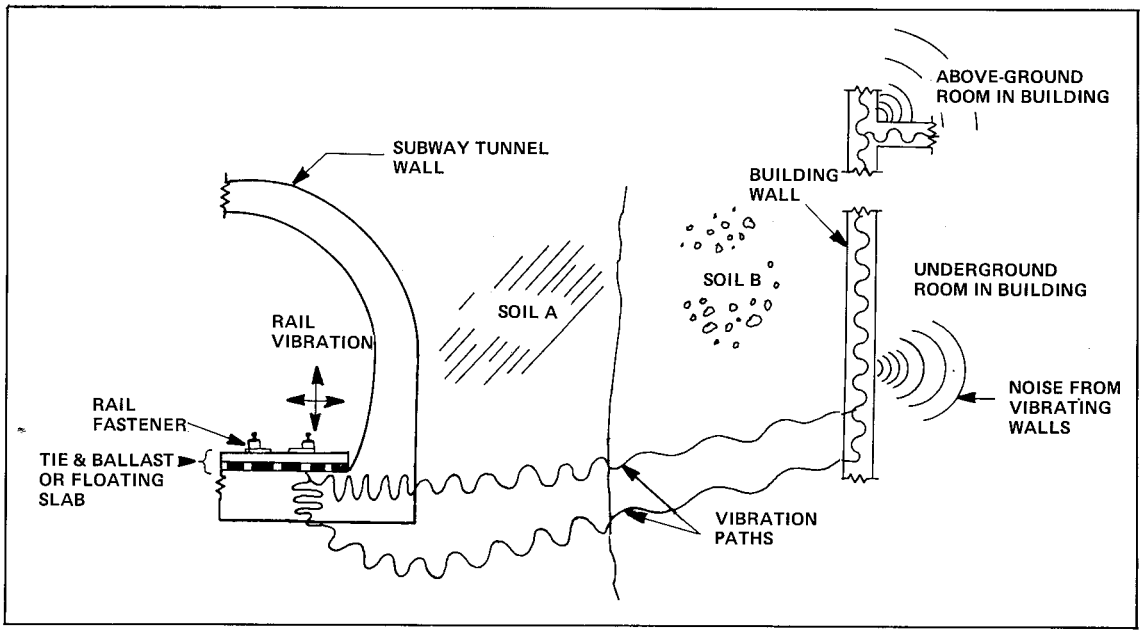


Figure 14. Schematic View of Propagation of Subway Vibrations into Buildings

Groundborne Noise From Subways

In underground portions of transit systems, vibrations generated by wheel/rail interactions are transmitted to the tunnel structure and then to the surrounding soil. The vibrations propagate through the soil to adjacent buildings, resulting in vibration of the floors and walls and secondary radiation of noise into the rooms. Figure 14 shows typical propagation paths of subway vibrations into buildings. Before the vibration levels are high enough to be felt, the secondary noise radiation due to a passing train can be heard as a low rumbling sound or as rattling sounds from objects in a room, such as windows or dishes.

Groundborne noise and vibration is a source of considerable annoyance, and a major source of community complaints received by transit authorities. It is one of the largest sources of complaints to the NYCTA. More cost-effective methods for prediction and control of groundborne noise and vibration are needed to alleviate this problem.

Development of Analytic Models for Groundborne Noise

The review of prediction and control techniques for urban rail transit noise and vibration, mentioned under the previous section on elevated structure noise, also provided the groundwork for subsequent research on groundborne noise and vibration. (24) The study found that current techniques for the prediction of groundborne noise and vibration were inadequate.

Research currently underway will attempt to improve noise and vibration prediction. A comprehensive mathematical model to predict the propagation of vibration from the subway structure to adjacent buildings is needed. In particular, the propagation of sound waves through the earth surrounding the tunnel requires further investigation. Researchers will draw upon the expertise of practitioners in the fields of rail transit noise and vibration control, geophysics, soil and rock mechanics and structural dynamics, including soil/structure interaction, to develop the model. Various analytic and empirical models have been developed already

in relation to different aspects of the transmission of groundborne noise and vibration. The current project will refine and expand these models and will conduct further research to fill gaps in existing knowledge. The various models will be combined into an overall prediction model which will permit variations in the type of track (rail, rail fastening method, and trackbed), tunnel structure, surrounding earth, and building structure as a basis for prediction. Groundborne noise and vibration has been found to vary considerably from one transit system to another. Existing measurements of noise and vibration from the different systems will be collected into a data base which will be used to validate the prediction model, and to identify those factors which account for the variability between systems.

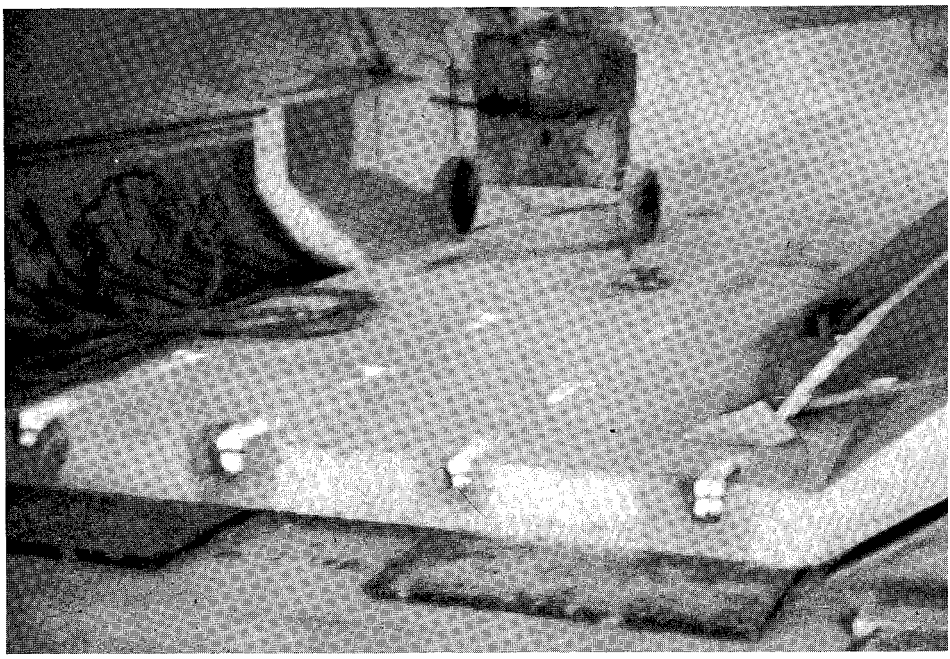
Groundborne noise and vibration control techniques will be surveyed and evaluated. The most promising techniques will be selected for further refinement. Using the prediction model, design modifications will be made in order to optimize the vibration control. maintenance costs, and the sa niques will also be assessed. Fin dations for in-service testing techniques will be made.

Groundborne Noise Treatments

Based on research done to ing techniques appear to be t priate for reducing groundbor bration. As in the case of ele vibration, any reduction in vib during wheel/rail interaction w reduction in vibration transmitte Wheel truing, rail grinding, and t in place of jointed rail are all cap groundborne vibration in this v

Another type of treatmen the amount of vibration trans rails to the roadbed. Ballast, w crushed rock placed between t

Concrete floating slab trackbed supported on resilient pads reduce vibrations tra tunnel.



roadbed, acts in this way. Ballast can also reduce in-car noise levels in tunnels due to its absorptive properties. However, the use of ballast may require a larger tunnel diameter and hence not be feasible.

Resilient rail fasteners, which involve the placement of a resilient layer of material between track and roadbed, act to reduce the transmission of vibration. The "softer" or more resilient the fastener, however, the more likely it will produce track alignment or stability problems. Softer fasteners may also allow rails to vibrate more freely and possibly increase tunnel noise levels, while at the same time decreasing vibrations transmitted to the roadbed.

Resiliently mounted "floating slab" track beds appear to be a more effective technique for reducing vibration transmission. This method consists of rail mounted on concrete trackbed slabs isolated from the tunnel floor by resilient pads. Figure 14 shows a typical floating slab trackbed. Floating slabs are capable of reducing vibrations transmitted to the tunnel wall by 10 to 20 dBA over resilient fasteners or ballasted track. Disadvantages include the expense and the need for a larger tunnel in some cases.

Trenches dug along the sides of tunnel walls can act as a barrier preventing the transmission of vibration to adjacent buildings. However, there are practical drawbacks to this technique, in particular the need for very deep trenches to attain effective vibration reduction.

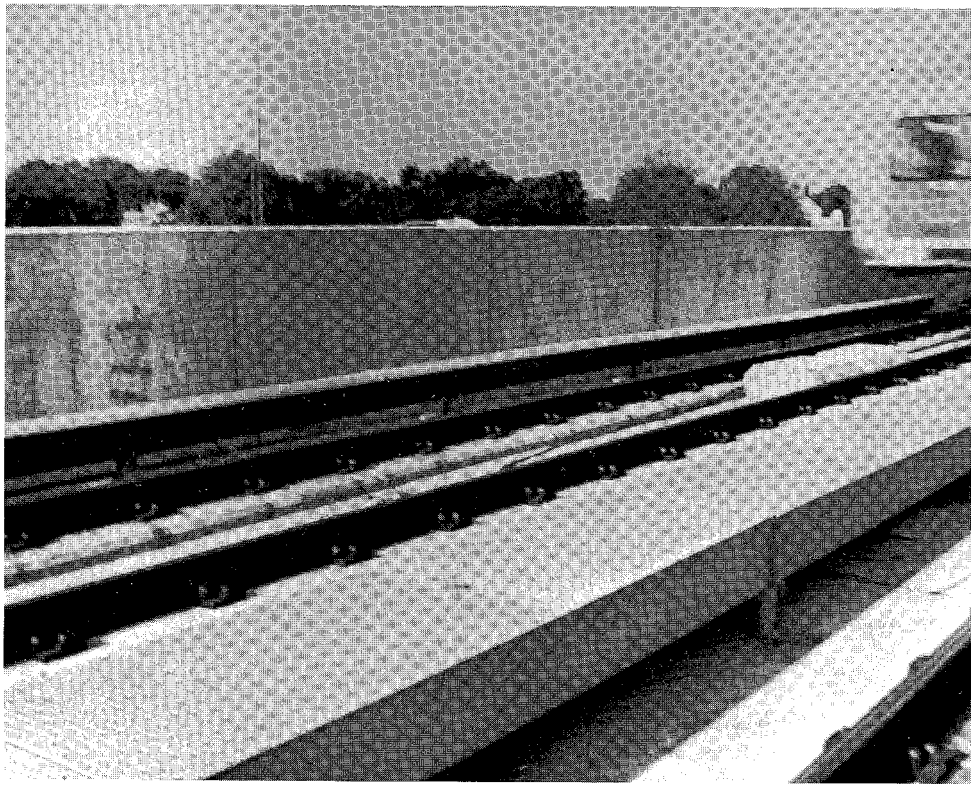
Although floating slabs represent the most effective technique for reducing the transmission of vibration, their installation is currently expensive, and more cost-effective designs are needed. To address this need, research on the use of floating slabs has been conducted. (30) A model was developed to predict the reduction in vibration transmitted from the rails to the tunnel floor obtained with floating slabs. A second part of the research effort involved a field study of floating slab track undertaken in cooperation with the NYCTA. The effectiveness of floating slabs in reducing vibration transmitted to the tunnel floor and walls was evaluated. Data collected included measurements at several points on the slab, on the tunnel wall, and on the tunnel floor. Vibration levels produced along floating slab track were compared with those produced along conventional track for the same train passbys. One of the study findings was that "floating ties," which consist of heavy concrete ties supported by resilient materials on the tunnel floor, could be just as effective as continuous floating slab.

A number of rail fastening systems are currently available commercially. To provide a basis for selection among these systems, a study is now being formulated which will compare the cost and performance of various systems. The acoustic and vibration characteristics of the following systems will be compared: standard wood ties on ballast, wood blocks cast into the concrete invert (tunnel floor), concrete ties on ballast, resiliently supported concrete ties, and resilient fasteners directly fixed to a concrete tunnel floor. Data on each of these systems also will be compared with the data previously obtained on the performance of floating slab track systems.

Propulsion System Noise

Noise from the operation of propulsion system equipment, particularly traction motors and gearboxes, is now recognized as a substantial contributor to urban rail transit noise. Noise from the propulsion system, particularly from the motor cooling fans, increases with train speed more rapidly than does wheel/rail noise. Recent tests on SEPTA and NYCTA have indicated that on older model transit cars, propulsion system noise can exceed wheel/rail noise at speeds as low as 30 mph. On newer systems where continuous welded rail and other wheel/rail noise abatement techniques are employed and where train operating speeds are typically higher, propulsion system noise is again often the dominant noise source.

Research is planned to develop and demonstrate a technology for retrofitting existing vehicles in order to abate propulsion system noise. This will be accomplished through a three-phased effort: first, the specific noise-generating



Barrier walls used on new systems help reduce the impact of propulsion system nois side community.

sources in propulsion systems will be identified; second, various techniques for controlling these sources will be evaluated; and finally, the best techniques will be demonstrated through in-service testing.

Several techniques to control the propagation of propulsion system noise away from concrete elevated structures were recently investigated. The new transit system under construction in Dade County, Fla., includes extensive mileage on concrete elevated structures. Indications from recent studies are that propulsion system noise levels on concrete elevated structures are 5 dBA higher than levels on at-grade ballasted track due to a lack of absorptive materials under the car. Dade County is planning to use acoustical barriers to reduce noise levels along elevated structure route mileage. However, it was believed that the use of v might provide a more cost-effe Vehicle skirts, which extended body down over the wheels, act radiation from the undercarriage

A study was undertaken by U tigate the relative effectiveness niques and to obtain technical info in future propulsion system noise Results of scale model tests show skirts in combination with under treatment provide 5 dBA reduct sion system noise on concrete e tures. Based on these initial estimated that the use of vehic undercar absorption in Dade Cou the need for acoustical barriers in in potential savings of $3 million.

3. Technology Deployment

The primary goal of the Urban Rail Noise Abatement Program is the deployment or implementation of cost-effective noise abatement techniques on U.S. transit systems. In order for research and development activities to result in implementable products, on-going communication must be maintained with potential users and suppliers of noise abatement treatments. Periodic review of research and development activities by users and suppliers can provide valuable input in the form of technical, operational, and economic data to guide research and development activities in a productive manner.

The participation of APTA in an advisory capacity in the Urban Rail Noise Abatement program provides one method of communication with the U.S. transit industry. The APTA Advisory Board, with representatives from all 10 urban rail transit properties, meets approximately twice a year. The board reviews draft documents and final reports of program activities. In addition, APTA and UMTA jointly sponsor a seminar at the completion of each major research and development project to present project results. Attending these seminars are Advisory Board members, equipment suppliers, public officials, and consultants. The results of the SEPTA in-service testing of wheel/rail noise abatement techniques were presented in Atlanta, GA, in December 1979. A slide-tape show on the in-service testing was part of the presentation.

Research results are also disseminated through technical reports, distributed by UMTA to transit properties, consultants, government officials, and suppliers. The general public may obtain these reports through the National Technical Information Service (NTIS).

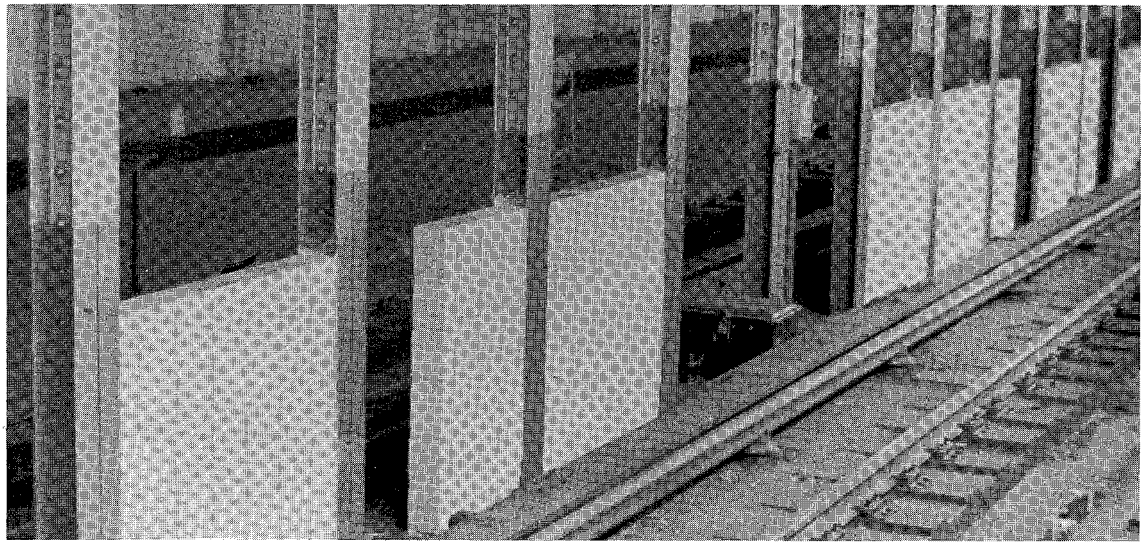
Newly-constructed systems are designed to include current noise abatement treatments.

A more direct exchange of information between UMTA and transit properties is planned through a traveling road show, which will visit all the major transit properties. Attending these meetings will be transit management and technical personnel, and members of the general public. Audio-visual presentations will be used to describe program activities and to explain the urban rail noise generation process. Various technical, planning, and institutional factors affecting implementation of noise abatement techniques will be discussed among those attending. UMTA/TSC staff will have an opportunity to learn about local experiences with noise abatement while at the same time disseminating information on program-sponsored activities.

The Department of Transportation's Transportation Systems Center (TSC) will play an increasing role in the exchange of information on urban rail noise abatement. In the past TSC has planned and implemented the research program and has acted as technical monitor for research projects funded through the Urban Rail Noise Abatement Program. In this capacity, TSC staff have also provided technical assistance on noise abatement to transit properties and have acted as an informal clearinghouse on urban rail noise abatement information. TSC is currently formulating a plan to collect, store, and retrieve pertinent information regarding urban rail noise activities. Organizations involved include transit properties — both domestic and foreign — consultants, universities, suppliers, private companies, community organizations, and government agencies. The first phase of this information program will utilize a library-type filing and retrieval system. The second phase will utilize a computerized data base management system. Additionally, TSC will maintain a technical data information file and a catalogue of technical references. All of this information will be available to those working in the area of urban rail noise abatement.

The actual implementation of noise abatement programs by transit authorities presents various technical and institutional difficulties. Under the Urban Rail Noise Abatement Program, several tools are being dev
noise abatement planning and i
The profusion of recent literatur
cult for transit authorities to se
ment available technology f
vibration control. A *Handbook*
Noise and Vibration Control is b
to summarize the literature in a
transit authorities, as well as b
consultants. Topics covered inc
tals of sound and vibration, mea
niques, acceptability criteria,
actions required for new and for
techniques recommended for co
station, wayside, elevated structu
borne noise and vibration, as wel
histories of noise control actions
different transit authorities. Two
handbook are planned. The first,
in 1980, will summarize the most
sit noise control data and proce
available. A second edition w
update the first to include futur
program. In each case, the handb
tributed at an invitational semin
the content will be discussed an
will be suggested.

Noise abatement planning is
solely upon the state of availab
technology. The planning of such
is influenced by the concerns of
ties, the public, and various loca
eral agencies, as well as by avail
order to aid transit authorities i
efforts, a *Noise Abatement Plan*
is being prepared which will ider
the elements necessary for
noise abatement planning, des
resources, e.g. computer plan
potential funding sources, and p
case histories of noise control pla
authorities. As part of this activ
program is being developed whi
determination of the most cost-e
wide noise abatement strategie
dure for the Evaluation of Ab
Effectiveness" (acronym PEAC
the cost-effectiveness methodo



Older stations can be acoustically upgraded with installation of noise control treatments such as sound-absorbing barriers, resilient rail fasteners, and welded rail.

as part of the assessments, in particular a refinement of this methodology done for the NYCTA.

In addition to the handbooks, a *Compendium of Acoustical Materials* for use in rail transit systems is planned as an aid to transit operators responsible for implementation of noise control.

The exchange of technical information with others engaged in urban rail noise abatement research and research in related fields, such as acoustics, is an important component of the research and development process. Participation by TSC personnel in various professional and trade organizations is one means to this end. In the past TSC personnel have presented papers at the International Conference of Noise Control Engineering (INTER-NOISE) and at the National Conference of Noise Control Engineering (NOISE-CON), as well as participating in two International Workshops on Railway and Track Transit System Noise. Representation on the Noise Committee of the International Union of Railways has been a valuable source of information on European railway noise research. The publication of research results by TSC personnel in technical journals provides another avenue of communication.

The greater the overall awareness about the activities of the Urban Rail Noise Abatement program, the more effective the program can be. The traveling road show, described earlier, will acquaint broader numbers of people with the program. Other efforts to publicize the program include a brief program summary and this state-of-the-art overview.

Inquiries about program activities, products, and future plans are invited and should be directed to:

Robert Hinckley, Program Manager.
Transportation Systems Center
U.S. Department of Transportation
Kendall Square
Cambridge, MA 02142
(617) 494-2185
or
Paul Spencer, General Engineer
Office of Rail and Construction Technology
Urban Mass Transportation Administration
U.S. Department of Transportation
Wshington, D.C. 20590
(202) 426-0090

Glossary

APTA
American Public Transit Association

A-weighted decibel
A measure of sound which weights the various frequencies comprising a sound in a manner which approximates the perceptions of the human ear.

BART
Bay Area Rapid Transit District

Bogie
A transit car undercarriage which swivels so that curves can be negotiated

Crabbing
An alternate rolling and sliding of the wheel along the rail which occurs as a train rounds a short radius curve

CTA
Chicago Transit Authority

Damped wheels
Standard wheels retrofitted with a damping device to reduce vibrations

dBA
See A-weighted decibel

Dynamic braking
Use of the traction motors as generators, thus creating a drag on the train

Floating ties
Heavy concrete ties supported by resilient materials on the tunnel floor

Floating slab track
Rail mounted on concrete slab trackbed which in turn is isolated from the tunnel floor by resilient pads

Girders
The horizontal beams of an elevated structure, which act as the main support for the roadbed

Impact noise
An impulsive noise produced by wheels encountering discontinuities, such as rail joints or flat spots on the wheels themselves

Jointed rail
Rail laid in segments producing a slight gap in the rail where segments meet

L_A(MAX)
The maximum A-weighted sound level occurring over a period of time.

MBTA
Massachusetts Bay Transportation Authority

NYCTA
New York City Transit Authori

PATCO
Port Authority Transit Corpora

PATH
Port Authority Trans-Hudson

Rail corrugation
Periodic irregularities in the rail during wear

Rail joint
The point at which the ends of

Resilient rail fastening
A method of rail fastening where material are placed between roadbed

Resilient wheel
A wheel manufactured with a re tween the tire and hub that acts

Ring-damped wheels
Standard wheels retrofitted to r means of a metal ring snapped i the wheel tread

Roar noise
A continuous noise caused by ness on wheels and rails

Route miles
Mileage measured according to transit line regardless of the nu

RTA
Greater Cleveland Regional Tra

SEPTA
Southeastern Pennsylvania Tr thority

SIRTOA
Staten Island Rapid Transit Ope

Squeal noise
A sharp high-pitched noise proc nate sticking and slipping of wh through short radius curves

Step-down joint
A rail joint where the second rail tion of the train's travel) is lower

Step-up joint
A rail joint where the second rail tion of the train's travel) is highe

Tangent track
Straight track

Tread braking
Application of brake shoes to the outer surface of the wheel in order to slow the train down

Truck
The frame and wheel assembly which supports the transit car body, with one truck at each end of the car

Tunnel invert
Concrete tunnel floor with a recessed area which contains the track

Wayside noise
Noise experienced in communities located along side transit rights-of-way

Welded Rail
Rail with a continuous unbroken surface due to the welding together of the ends of rail segments

Wheel flats
Flat spots on the wheel's rim caused by locking of the wheel during braking

Wheel squeal
See Squeal noise

Wheel truing
Machining wheel tire surfaces to remove irregularities created during train operations

Bibliography

NATIONAL TECHNICAL INFORMATION SERVICE

Reports on UMTA research and development described in this volume are available to the public through the National Technical Information Service (NTIS). NTIS is the principal repository and disseminating agency for all reports issued in conjunction with federal research and development activities. To order reports from NTIS use the order numbers ("PB" numbers) listed after each report citation in the bibliography. The lack of an order number following the citation means that the report had not yet been entered into the NTIS system when this publication went to press.

Inquiries about the availability or price of reports should be addressed to NTIS, rather than UMTA. The NTIS Order Desk telephone number is (703) 557-4650. Payment must accompany orders; cash, check, postal money order, GPO coupons, or American Express are acceptable. It is possible to establish an account at NTIS, from which payments are withdrawn when documents are ordered.

The NTIS purchase price includes postage at the fourth class rate. Three to five weeks must be allowed for delivery. Much faster delivery is provided by the NTIS telephone Rush Order Service (703) 557-4700, for an additional charge of $10.00 per document if mailed or $6.00 if picked up at NTIS offices in Springfield, Va., or downtown Washington, D.C.

1. "Computer-Assisted Planning for Rail Transit Noise Control" in **INTER-NOISE 76**, Proceedings of the 1976 Intenational Conference on Noise Control Engineering R. Lotz, U.S. DOT, Transportation Systems Center, April 1976.
2. **Development of an Acoustic Rating Scale for Assessing Annoyance Caused by Wheel/Rail Noise in Urban Mass Transit**. T. J. Schultz, Bolt, Beranek, and Newman, Inc., February 1974. UMTA-MA-06-0025-74-2, PB-231-363.
3. "Groundborne Noise and V
Underground Rail Systems"
of Sound and Vibration,
L. G. Kurzweil, U.S. DOT,
Systems Center, October 8,
4. "In-Service Testing of Wh
Control Treatments," paper
the 1978 APTA Rapid Trans
Chicago, June, 1978. L. G. K
DOT, Transportation Syster
5. **In-Service Performance a
Methods for Control of Ur
tem noise — Experimental**
Holowaty of DeLeuw Cather
and H. J. Saurenman and S
Wilson, Ihrig and Associate
UMTA-MA-06-0025-76-4, PB
6. **In-Service Performance a
Methods to Control Urbar
Noise — Test and Evaluati**
Holowaty of DeLeuw Cather
and H. J. Saurenman of Wil
Associates. April, 1977. UMT
10, PB-272-521.
7. **In-Service Performance a
Methods to Control Urbar
Noise — Initial Test Series**
Shipley of DeLeuw Cather a
and H. J. Saurenman of Wi
Associates. August, 1978. U
0025-78-7, PB-288-838.
8. **In-Service Performance a
Methods to Control Urbar
Noise — Second Test Se**
H. J. Saurenman, Wilson, Ih
ciates and DeLeuw, Cather a
October 1979. UMTA-MA-06
9. **In-Service Performance a
Methods to Control Urbar
Noise — Final Report.** H.
and G. P. Wilson of Wilson, I
ciates and R. L. Shipley of D
and Company. December
MA-06-0099-80-1.

10. "A Methodology for Determining Minimum Cost Rapid Transit Noise Control" in **NOISE-CON 73**, Proceedings of the 1973 National Conference on Noise Control Engineering. R. Lotz and L. G. Kurzweil, U.S. DOT, Transportation Systems Center. October, 1973.

11. **National Assessment of Urban Rail Noise,** G. Chisholm et al. U.S. DOT, Transportation Systems Center. March, 1979. UMTA-MA-06-0099-79-2, PB-295-752.

12. **Noise Abatement in Rail Rapid Transit: Effect of Some Variations.** W. R. McShane and S. Slutsky, Polytechnic Institute of New York. December, 1978. UMTA-NY-11-0002-79-2, PB-292-032.

13. **Noise Abatement Options and Costs for the CTA Rail Rapid Transit System (Draft).** R. Primer and M. L. Silver, University of Illinois. March, 1976.

14. **Noise Assessment and Abatement in Rapid Transit Systems — Report on the MBTA Pilot Study.** L. G. Kurzweil, R. Lotz, and E. G. Apgar, U.S. DOT, Transportation Systems Center. September 1974. UMTA-MA-06-0025-74-8, PB-238-113.

15. **Noise Assessment of the Bay Area Rapid Transit system.** S. L. Wolfe, P.Y.N. Lee, and H. J. Saurenman, Wilson, Ihrig, and Associates. October, 1978. UMTA-MA-06-0025-78-10, PB-292-397.

16. **Noise Assessment of the Chicago Transit Authority Rail Rapid Transit System.** M. L. Silver et al, University of Illinois. January, 1979. UMTA-MA-06-0025-79-8, PB-292-834.

17. **Noise Assessment of the Greater Cleveland Regional Transit Authority Heavy Rail Transit System.** R. H. Spencer and E. G. Hinterkeuser, Boeing Vertol Company. October, 1978. UMTA-MA-06 0025-78-12, PB-292-331.

18. **Noise Assessment of the New York City Rail Rapid Transit System.** W. R. McShane, S. Slutsky, and M. F. Huss, Polytechnic Institute of New York. January 1979. UMTA-MA-06-0025-79-7, PB-292-498.

19. **Noise Assessment of the Port Authority Transit Corporation, Lindenwold Rail Transit Line.** R. H. Spencer and E. G. Hinterkeuser, Boeing Vertol Company. October 1978. UMTA-MA-06-0025-78-9, PB-292-319.

20. **Noise Assessment of the Southeastern Pennsylvania Transportation Authority Heavy Rail Transit System.** R. H. Spencer and E. G. Hinterkeuser, Boeing Vertol Company. October, 1978. UMTA-MA-06-0025-78-22, PB-292-320.

21. **Noise Degration Over Time in Rail Rapid Transit Cars.** S. Slutsky, W. R. McShane, and J. J. Starace, Polytechnic Institute of New York. December, 1978. UMTA-NY-11-0002-79-1, PB-292-031.

22. "Noise Exposure Study of the Massachusetts Bay Transportation Authority Rapid Transit System" in **NOISE-CON 73,** Proceedings of the 1973 National Conference on Noise Control Engineering. E. G. Apgar and T. J. Trella, U.S. DOT, Transportation Systems Center. October, 1973.

23. **Noise in the New York City Transit System: Abatement Methodology and Cost Estimate (Draft).** W. R. McShane and S. Slutsky, Polytechnic Institute of New York. October, 1975.

24. **Noise Prediction Models for Elevated Rail Transit Structures.** J. E. Manning et al, Cambridge Collaborative, Inc. August, 1975. UMTA-MA-06-0025-75-12, PB-244-509.

25. **Noise Rating Criteria for Elevated Rapid Transit Structures.** T. J. Schultz, Bolt, Beranek, and Newman, Inc. May, 1979. UMTA-MA-06-0099-79-3, PB-297-419.

26. **Prediction and Control of Noise and Vibration in Rail Transit Systems.** L. G. Kurzweil and R. Lotz, U.S. DOT, Transportation Systems Center. September, 1978. UMTA-MA-06-0025-78-8, PB-294-968.

27. "Prediction and Control of Noise from Railroad Bridges and Trackbed Transit Elevated Structures" in **Journal of Sound and Vibration,** Vol. 51, No. 3. L. G. Kurzweil, U.S. DOT, Transportation Systems Center. April 8, 1977.

28. **Prediction and Control of Rail Transit Noise and Vibration, A State-of-the-Art Assessment.** J. E. Manning, G. C. Cann, and J. J. Fredberg, Cambridge Collaborative, Inc. April, 1974. UMTA-MA-06-0025-74-5, PB-233-363.

29. "Prediction of Community Noise from Rail Systems" in **Community Noise,** Special Technical Publication #692 of the American Society of Testing and Materials. L. G. Kurzweil, U.S. DOT, Transportation Systems Center. 1979.

30. "Prediction of Wayside Noise from Rail Transit Vehicles" in **INTER-NOISE 74,** Proceedings of the 1974 International Conference on Noise Control Engineering. J. E. Manning of Cambridge Collaborative, Inc. and L. G. Kurzweil of U.S. DOT, Transportation Systems Center. October 1974.

31. "Propagation of Noise from Rail Lines" in the **Journal of Sound and Vibration,** Vol. 66, No. 3. L. G. Kurzweil, W. N. Cobb, and R. P. Kendig, U.S. DOT, Transportation Systems Center. October 8, 1979.

32. "Railroad and Rail Transit Noise Sources" in the **Journal of Sound and Vibration Control,** Vol. 51, No. 3., R. Lotz, U.S. DOT, Transportation Systems Center. April 8, 1977.

33. "Rail Transportation Noise" in the **Handbook of Noise Control,** 2nd edition. R. Lotz and L. G. Kurzweil, U.S. DOT, Transportation Systems Center. McGraw Hill, 1979.

34. **Rail Transit Noise Abaten mum Cost; Assessment o Noise Climates and Abate (Draft).**S. L. Wolfe and R. H. ing Vertol Company. March

35. **Rapid Transit System Nois Program.** E. G. Apgar, U.S. Transportation, Transporta Center. January 1972. UMTA-72-4.

36. **Research Requirements S Rapid Rail Industry.** T. MITRE. September, 1970. U 71, PB-204-438.

37. "SEPTA Noise Control — T uation," paper presented at t Rapid Transit Conference, M 1979. H. J. Saurenman and C Wilson, Ihrig and Associat Kurzweil of the U.S. DOT, T Systems Center.

38. **Urban Rail Noise Abatem A Description.** L. G. Kurzw Cobb, U.S. DOT, Transport Center. March 1979. UMTA 79-1, PB-295-545.

39. **Vibration Prediction Mod ing Slab Rail Transit Trac** ning, D. C. Hyland, and G bridge Collaborative, Inc. UMTA-MA-06-0025-75-13, PB

40. **Wheel/Rail Noise and Vib trol (Interim Report).** P. J. al, Bolt, Beranek, and Newm 1974. UMTA-MA-06-0025-7 012.

41. **Wheel/Rail Noise and Vib trol (Final Report), Vol. I.** ton, M. J. Rudd, and I. L. Ver and Newman, Inc. May, 1975. 06-0025-75-10, PB-244-514.

42. **Wheel/Rail Noise and Vibration Control (Final Report), Vol. II.** P. J. Remington, M. J. Rudd, and I. L. Ver, Bolt, Beranek and Newman, Inc. May 1975. UMTA-MA-06-0025-75-11, PB-244-515.

43. "Wheel/Rail Noise: A Progress Report" in **INTER-NOISE 74**, Proceedings of the 1974 International Conference on Noise Control Engineering. R. Lotz, U.S. DOT, Transportation Systems Center. October 1974.

44. "Wheel/Rail Noise Reduction in Practice" in **INTER-NOISE 77**, Proceedings of the International Conference on Noise Control Engineering. R. Lotz, U.S. DOT, Transportation Systems Center. March 1977.

45. **Noise Control for Rapid Transit Cars on Elevated Structures: Preliminary Investigation of Vehicle Skirts, Undercar Absorption and Noise Barriers.** C. E. Hanson et al., Bolt, Beranek and Newman, Inc. April 1980. UMTA-MA-06-0099-80-4, PB80-213 071.

46. **Noise Impact Inventory of Elevated Structures in U.S. Urban Rail Rapid Transit Systems (Interim Report).** D. A. Towers, Bolt, Beranek and Newman, Inc. September 1980. UMTA-MA-06-0099-80-5, PB81-120 958.

47. **Wayside Noise of Elevated Rail Transit Structures: Analysis of Published Data and Supplementary Measurements (Interim Report).** E. Ungar and E. Wittig, Bolt, Beranek and Newman, Inc. December 1980. UMTA-MA-06-0099-80-6.

48. **Wheel/Rail Noise Control — A Critical Evaluation (Interim Report).** L. G. Kurzweil and L. E. Wittig, Bolt, Beranek and Newman, Inc. January 1981. UMTA-MA-06-0099-81-1.

49. **Vibration Level Data Brighton-New York City Transit Authority (Final Report).** E. J. Rickley and N. E. Rice. U.S. DOT, Transportation Systems Center. February 1981. UMTA-MA-06-0099-81-2.

50. **Evaluation of Squeal Noise from the WMATA Transit Car Disc Brake System: A Preliminary Investigation (Final Report).** L. A. Ronk and M. A. Staiano, ORI, Inc. March 1981. UMTA-MA-06-0099-81-4.