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RAPID TRANSIT SYSTEM NOISE ABATEMENT PROGRAM

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PROGRAM PLAN

Prepared for:
DEPARTMENT OF TRANSPORTATION
URBAN MASS TRANSPORTATION ADMINISTRATION
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16. Abstract

This program plan describes a broad program for the reduction of noise and vibration in rapid transit systems, which impacts the patrons and inhabitants of the nearby community. An UMTA/TSC survey has provided data on the most urgent needs and state-of-the-art techniques. Demonstrations of such techniques in operational form on transit systems are described in areas of wheel squeal, concrete floating slab, wayside sound and vibration barriers, elevated structure improvements, station and tunnel acoustics, rail joints and fastenings and yard noise abatement. The four year program described will provide outputs on the feasibility of the techniques tested and design criteria for use by the industry on existing system improvements and for specifications on new ones.

17. Key Words	18. Distribution Statement
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SUMMARY

A preliminary survey of transit authorities, consultants, and the literature by TSC has confirmed the urgent need to improve and expand noise abatement efforts in rapid transit systems throughout the United States. TSC has prepared, based on the results of questionnaires sent to the major rapid transit authorities, and discussions with cognizant officials, engineers, and technical personnel in the industry, an aggressive UMTA program plan to: (1) detail the major problem areas, (2) undertake field demonstration projects to alleviate those problems which are amenable to early solution along with developmental projects to solve those problems for which noise reduction techniques are not now available, and (3) include an active follow-on program to insure that the technological advances achieved in this program are applied widely. This proposal explains the background justification for a UMTA noise abatement program, some of the initial findings of the work carried out to date at TSC, a listing of priority problems, and a description of a four-year program plan. Interim outputs of this plan will include a state-of-the-art (SOA) summary for industry-wide guidance, practical specifications regarding noise levels goals commensurate with the current state-of-the-art and existing municipal noise codes and standards, and immediate initiation of one high-priority noise control demonstration--wheel-rail squeal abatement.

The estimated cost for the proposed four-year program is $3,060,000 split by fiscal years as follows: FY 1972, $200K; FY 1973, $910K; FY 1974, $1200K, and FY 1975, $750K. The estimates for FY 1974 and 1975 are preliminary estimates only, at this time. As the exact nature of each of the subsequent demonstration projects is detailed from information collected in the state-of-the-art survey, more precise funding requirements will be obtained. The structure of this program is presented in tabular form on the following few pages and later in the Schedule section.

The results of the proposed program will provide significant benefits to the public through immediate reduction of noise in the demonstration projects, followed by more widespread reductions in transit system noise levels as the successful techniques are implemented elsewhere. Successful noise abatement will provide significantly improved passenger comfort and system acceptability to the public, as well as indirect economic benefits to the transit authorities and surrounding real estate values.

Site selection and coordination with transit properties will be an important part of the program. Also, careful consideration will be given to the method of funding, that is, whether to work directly with the transit property for a given demonstration or contract with an outside engineering firm.

Table 1 provides a summary of the demonstrations with cost and schedule data.

TABLE 1. TASK SUMMARY

Task	Cost FY	Start/Finish Dates	Reports & Milestones	Purpose & Utilization	Output
1. State of Art Survey	FY 72 $70K FY 73 $70K	April 72/ April 73	Interim Report Oct. 7 Final Report April 73 Update Reports 74, 75	1. Collect in one document information on available design and analytical techniques. 2. Guide overall program needs and indicate required innovations. 3. Collect information on best sites for demonstrations.	1.SOA Design Report 2. Report on needs of properties and feasible improvements. 3. Advanced Design Guidelines for Demonstrations.
2. Wheel Squeal Elimination Demonstration	FY 72 $120K FY 73 $170K	March 72/ May 74	Interim Report Sept. 72 Interim Demonstration Mar 73 Final TBD Demonstration May 74 Final Report TBD	1. Demonstrate feasibility of reducing squeal in operating system using one or more of: resilient wheels, wheel damping, solid lubricants, resilient rail covering. 2. Analysis of wheel stick, slip, vibration modes, stress, thermal effects, and compatibility with inspection and maintenance requirements. 3. Assist with measurements and analysis for systems engaged in wheel squeal reduction.	1. Comparison Data on different techniques, recommendations for optimum design of low squeal system. 2. Test results and design data of maximum value to industry.
3. Concrete Floating Slab Track Support	FY 72 $5K FY 73 $250K	May 72/ Dec. 74	Interim Report June 73 Complete Construction Dec 74 Final Report TBD	Construct "Best" slab based on improved design and construction techniques.	Performance data, and design and construction techniques for cloating slab.

TABLE 1. TASK SUMMARY (Cont.)

Task	Cost FY	Start/Finish Dates	Reports & Milestones	Purpose & Utilization	Output
4. Wayside Sound and Vibration Barriers	FY 73 $45K	November 73 TBD	Interim Report July 74 Complete Construction Mar. 74 Final Report TBD	Construct improved airborne sound and earthborne vibration barriers to protect wayside areas from transit noise and vibration.	Design and techniques and materials for optimum barriers for wide use by industry on noisey sections of tracks.
5. Elevated Structure Improvements	FY 73 $40K	Jan. 73/ TBD	Interim Report April 74 Final Report TBD	To quiet existing noisy elevated structures and future designs with improved barriers, roadbeads, and damping of structural resonance.	Techniques for reduction of elevated structure noise and vibration.
6. Station and Tunnel Acoustics Demonstration	FY 72 $5K FY 73 $160K	Mar. 72/ TBD	Contract Award September 73 Interim Report April 74 Interim Demonstration Sept. 74 Final Report TBD	Choose improved sound absorbing materials and apply to stations and tunnels to reduce noise impact on patrons.	"Best"choice of materials and techniques for noise reduction in tunnels and stations.
7. Rail Joints Fastenings, Special Track Work Demonstration	FY 73 $50K	April 73 TBD	Interim Report September 74	To reduce noise and vibration from joints and special track work.	"Best" choice of existing and new designs and alterations for joints, fastenings and track work.
8. Yard Noise abatement Demonstration	FY 73 $50K	April 73 TBD	Interim Report November 74	To apply wide variety of best abatement techniques to rail yards in sensitive neighborhood.	Development of "Quiet" yards for maintenance and switching.
9. Additional tasks based on SOA Survey	FY 73 $75K	April 73 TBD		To develop and apply promising new concepts from SOA Survey.	Advanced designs and hardware for transit industry.

BACKGROUND STATEMENT

General advances in the technology of the various transportation modes, increased understanding of noise and vibration phenomena, and growing concern over environmental deterioration in urban centers all combine to alter the status of rapid transit noise from that of a simple irritant to that of a serious problem. Continued exposure to high noise levels produces human stress, fatigue, and possibly irreversible hearing loss. From an economic viewpoint, noise-induced passenger discomfort can reduce patronage and system revenue. Bond issues for transit system expansions are jeopardized by negative attitudes created by noise and vibration. Reduced real estate values in surrounding neighborhoods lead to additional public reaction. And finally, excessive transit noise can drive passengers to other modes of transportation, especially the private automobile with the increasing problems of highway congestion and air pollution. Noise reduction is concerned with sound which can annoy and interfere with the functioning of the recipient. Considerable amounts of energy, time and money are invested in lighting, architectural aesthetics and ventilation while excessive noise which is potentially very harmful has been relatively neglected.

Noise levels of 90 dBA or more are considered dangerous to hearing in industrial work situations. Yet, noise levels in excess of 95 dBA[1,2] have been measured inside subway cars, peak values well in excess of 100 dBA have been measured on passenger platforms [1,3]. Such levels present serious risk of hearing damage [4]. The general problem of rapid transit system noise has been recognized for a long time, and a considerable body of literature exists on the subject. A variety of methods has been tried to reduce transit noise. Some of these methods have been judged useful and have evolved into common practice, while other methods have been considered ineffective and cast aside, possibly without firm basis for evaluation. In most cases, abatement success has been judged on a semi-empirical basis, rather than a critical analysis using valid procedures. Until very recently, progress in transit noise control, following trial-and-error procedures, has been quite slow. Modern engineering techniques and procedures are necessary to perfect many of the traditional methods of noise reduction and to develop new approaches.

Advanced state-of-the-art techniques, if optimized and demonstrated, for reducing external noise are:

1. Improved joints.
2. Careful configuration and maintenance of track bed, ties and ballast
3. Resiliently supported massive track slabs.
4. Sound absorbing materials in stations and tunnels.
5. Resilient rail fasteners and pads.
6. Airborne sound barriers
7. Periodic grinding and polishing of wheel and rail contact surfaces.
8. Resilient wheels
9. Wheel damping.
10. Reduction of unsprung mass.

Interior transit car noise can further be reduced by proper application of damping materials to auxiliary equipment, sealing of air gaps through exterior walls, and resiliently-mounted interior surfaces. Such techniques have been incorporated in the new BARTD cars with apparent good success. The Montreal subway system, using pneumatic rubber tires on concrete "rails" is still quieter. These two systems provide two examples of recent work which has successfully reduced objectionable rapid transit noise. However, a thorough, systematic analysis of potential noise and vibration reduction concepts, and large-scale demonstrations of such concepts, have yet to be accomplished. In view of the large financial expenditures being planned for improvement and expansion of existing transit systems and construction of new ones, it is important that an early effort commence to perfect existing successful noise reduction concepts, and to share useful technologies among the various transit systems.

A flexible viewpoint must be maintained in applying control techniques to vibration and noise sources in rapid transit systems. Considerations must be given to techniques for benefiting existing systems as well as those best suited to as yet unbuilt systems. While improvement of existing systems is urgent the most successful applications of acoustical and vibration engineering will be on these future systems. Also, economic and operational factors will affect decisions on the extent of such control desired.

The noise abatement work plan as presented in this proposal is based on a recent determination of the technological status of a number of rapid transit authorities in North America. These systems differ widely in terms of age, size, extent of noise/vibration problems, and amount of resources presently available for abatement work. The UMTA/TSC inquiry using a questionnaire (supplemented by meetings and telephone conversations) has provided a catalog of many of these factors in order to develop a meaningful program for a coordinated national effort in transit noise/vibration abatement.

Some highlights of this inquiry are presented below from several categories.

NOISE ABATEMENT QUESTIONNAIRE HIGHLIGHTS

Question:
1.1 What noise control problems have been (or will be) of concern?

Answers:
a. Cleveland - wheel rail noise, acceleration squeal, curve squeal and wheel flats.
b. Toronto - wheel/rail squeal, special trackwork noise/ vibration, insulated joints, noise/vibration in adjacent buildings, noise/vibration insulation of car body, frame and truck.
c. New York City - steel elevated structure noise/vibration to nearby buildings, airborne noise in stations and within cars.
d. BARTD - wheel/rail airborne noise to nearby buildings (anticipated).
e. PATH - wheel screech on sharp turns, noise from brakes and auxiliary equipment.
f. Chicago - wheel/rail squeal and rumble on elevated structures affecting riders and nearby residence, vibrations from elevates structures to nearby buildings.

Question:
1.4 What corrective measures would you like to see?

Answers:
a. Cleveland - correction of wheel/rail noise, curve and acceleration squeal and wheel flats.
b. Toronto - correction of noise/vibration in adjacent buildings, improvements in special trackwork rail cant, wheel taper, rail/wheel gauge, develop quiet car (interior).
c. New York City - improve maintenance of wheel/rail surface, improve rail configurations, install welded rails, resilient fasteners, floating slab track support, acoustic absorption treatment in stations, reduction of elevated structure noise, develop quiet car.
d. BARTD - elevated structure parapet barriers, resilient track fasteners, acoustic treatment of tunnels and track invert (both elevated and subway stations), floating slab track support in certain stations.
e. PATH - tests of flexible wheels and wheel damping treatments, rail/wheel lubrication tests.

f. Chicago - remodel station to include acoustical absorption treatment, reduce elevated structure, subways and car noise.

Question:
2.0 Rate noise sources in order of concern.

Answers:
a. Cleveland - wheel/rail interaction, brakes, switching yards, rail joints and switches, auxiliary equipment, tunnel noise, noise leaks in doors and windows.
b. Toronto - wheel/rail interaction, joints, switches, shops and yards for maintenance and switching, station design improvement, tunnel acoustics.
c. New York City - wheel/rail interaction, joints, switches, brakes, switching yards, propulsion and auxiliary equipment.
d. BARTD - wheel/rail interaction, propulsion and auxiliary equipment, rail joints and switches.
e. PATH - wheel/rail interaction, propulsion equipment noise, auxiliary car equipment, brakes, rail joints and switches.
f. Chicago - wheel/rail interaction, auxiliary car equipment, rail joints and switches, switching yards, maintenance shops and yards, propulsion equipment.

Question:
2.8 What noise control measures tried were successful?

Answers:
a. Cleveland - Paving of track invert moderately successful.
b. Toronto - Use of welded rail, grinding of wheels/rails, acoustic treatment of tunnels and station.
c. New York City - grinding of wheels/rails.
d. BARTD - grinding of wheels/rails, resilient rail fasteners, wheel damping, wayside airborne sound barriers, propulsion and auxiliary equipment acoustically treated, car floor and station platform acoustic treatment.
e. PATH - wheel damping and acoustical treatment of stations and track.
f. Chicago - rail grinding, installation of ballasted track in tunnels.

Question:
2.8(f) What problem needs prompt attention?

Answers:

a. Cleveland - acceleration squeal.
b. Toronto - wheel squeal on curves, noise from track discontinuities, car interior noise, noise and vibration outside subway structure.
c. New York City - wheel/rail grinding, rail joint maintenance.
d. BARTD - wheel flats.
e. PATH - wheel noise.
f. Chicago - subway tunnel and elevated structure noise.

DESCRIPTION OF WORK

The work program developed with the guidance provided by the above information falls naturally into three basic phases of effort:

1. Continuation of the present activity in surveying and cataloging the current state-of-the-art in rapid transit noise and vibration control through continued communication with transit authority personnel and consultants experienced in the field and examination of the successful noise abatement techniques. Following this data collection period, we will perform a diagnosis and analysis of recognized noise/vibration problems and potential control techniques. Finally, a classification of problems will be made in terms of those for which effective control techniques are currently available, those for which effective control techniques require further developmental work before demonstrations are warranted, and those for which further analysis will be required before developmental effort is warranted.
2. Demonstration projects to evaluate the most promising noise abatement techniques in service, beginning immediately with those problems for which effective control techniques are almost available, and also beginning developmental and analytical-developmental efforts for those problems for which effective control techniques are not immediately available. These demonstrations to be conducted in cooperation with selected transit authorities where the corresponding problems now exist, so as to produce beneficial results as soon as practicable.
3. Continued liaison with transit authorities and UMTA contractors to provide technical advice in noise control areas; drafting of training handbooks and conducting training seminars to insure wide desemination of the results of this program; assurance that standards and specifications recommended for UMTA use incorporate practical noise abatement factors; general provision of technical support to UMTA in noise control areas.

The specific tasks UMTA/TSC will address itself to are:

A state-of-the-art survey which is essential to draw on the successful techniques of individual transit systems, to discover recent advances in noise/vibration control not

adequately publicized or appreciated and to locate areas where new developments are urgently needed. This survey will build on the body of information recently collected such as the questionnaire results cited, the literature consulted, and results of meetings and discussions with many cognizant individuals in the transit industry. Where necessary, noise and vibration measurements will be made and visits made to appropriate properties, test sites and equipment manufacturing installations. The survey will yield an interim report in the early stages and a final, detailed, report necessary for the carrying out of the noise abatement program. This will also be of value as a working document for industry as a whole. Most important it will serve as a guide for demonstration site selection.

The state-of-the-art survey will lead to a period of diagnosis and analysis of transit system noise sources including topics such as: wheel squeal, wheel and rail roughness and correlation with manufacturing and maintenance procedures, rail joints, switches and cross-over hardware, macroscopic track irregularities (vertical and horizontal), propulsion units, brakes, ventilation systems, compressor units and other auxiliary equipment and current collectors. An analysis of propagation paths for airborne noise and soilborne vibrations will also be conducted. This will embrace topics such as acoustical leaks into car interiors, the acoustics of subway tunnels and stations, soilborne vibration to nearby building foundations, and airborne noise propagation to property along the wayside and under elevated structures.

Tables A1, A2 and A3 provide an outline of the present status of such knowledge.

A number of full scale demonstration projects of the most promising methods of control will be designed and put into practice. Emphasis will be on those appropriate to existing systems with a minimum interruption of service. With ingenuity, careful scheduling (making use of night time and weekend reduced service) and fortuitous by-pass tracks changes in tracks, inverts, ballast, fasteners, pads and other equipment can be made on revenue producing systems. In special cases resort will be had to the Pueblo test site for advanced or radical measures. The first demonstration will combine a number of the most feasible wheel squeal abatement means known. Resilient wheels, wheel resonance damping, wheel-rail lubrication, and resilient track coverings have all been tested and gave varied degrees of success. However, these techniques are still under study, have not provided a general solution and require further study and comparison. In addition, some hardware development and continuation of helpful theoretical analysis of wheel resonance modes and rail-wheel adhesion will supplement the effort. This demonstration will be started in the near future, before the state-of-the-art survey results

are in, as soon as the site selection and scope of the work have been determined.

Other demonstrations are planned in the areas of low frequency rail-wheel rumble, station and tunnel acoustics (barriers between tracks and absorbing material on walls, ceilings and under platforms), concrete floating slab road bed for vibration suppression, elevated structure noise and vibration abatement, airborne sound barriers, soilborne vibration barriers at grade-level near residential districts, and acoustical treatment of a typical outdoor maintenance or holding yard in a populated area. The exact choice of later demonstration projects, and cost estimates will be spelled out in subsequent sections and technical appendices.

Presently planned are the following demonstration projects (Figures 1 and 2):

- Wheel squeal reduction (Appendix C)
- Wayside sound and vibration barriers (Appendix D)
- Floating slab (Appendix E)
- Station and tunnel acoustics (Appendix F)
- Elevated structures improvement (Appendix G)
- Rail joints and fasteners (Appendix H)
- Yard noise abatement (Appendix I)
- Others based on state-of-the-art survey

It is understood that prior to the implementation of some demonstrations an intermediate stage of tests of hardware, new or off-the-shelf, will sometimes be necessary. As dictated by the state-of-the-art survey this might include rail fasteners, tie pads, components of resiliently mounted concrete track slabs, lighter weight wheels and trucks, durable sound absorbing materials for tunnels, stations and barriers (indoors and outdoors), shock absorbing auxiliary equipment mounts, ventilation duct noise attenuation, acoustic enclosures for auxiliary equipment, quiet mechanical brakes and quiet current collector contacts. Again, some analytic and design work will be necessary in special cases to permit the optimum choice of design in the case of competing options. In particular, need exists for further analysis of barrier designs for airborne noise and soilborne vibrations, analysis of optimum parameters of resiliently mounted concrete slabs for each special installation required. The details of these hardware and analytic tasks are described in the appendices.

A continual liaison with the transit authorites and UMTA contractors will parallel these efforts. TSC is only one of a number of groups with the common goal of transit system improvement. However, as a government agency with in-house technical capability we can fill a unique role for UMTA by

providing spot technival advice, assist in the formulation of specifications and guidelines for noise control codes, and organize training seminars for the disemination of our own results from this program and reports from other groups.

The need to coordinate the UMTA/TSC transit noise abatement program with the on-going rehabilitation and improvement efforts at the various transit properties leaves some required work which is not described in the above categories. Several transit properties are making in-house efforts at noise abatement by improving tracks and roadbed, testing resilient wheels, acoustically treating a station, and ordering new more quiet cars. Frequently, they lack funds and expertise in noise abatement to carry out appropriate noise and vibration measurements and data analysis so as to arrive at objective decisions as to the effectiveness of such improvements to guide future planning. TSC has had requests for advice and assistance in this measurement work and can arrange to provide such services where they fit within the scope of their abatement program. An example is the Boston MBTA forthcoming program to test eight resilient wheels of the Penn Cushion Company on the Green Line street car route. These are being installed on a car for testing the reduction in wheel rail noise under a variety of conditions - underground, grade level and on steel elevated structures with sharp curves. This test will provide data for decisions on acquiring larger numbers of such wheels and therefore must be well designed and carried out with specialized equipment and personnel. TSC will provide preliminary assistance under this noise abatement program and then make arrangements for extended measurements and analysis for a thorough test program.

Another area where TSC noise abatement capability has been called on and will continue in demand is to provide informal technical advice to transit equipment industry representatives engaged in UMTA funded new equipment development. An example is the Boeing Vetrol Urban Rapid Rail Vehicle and Systems Program where a state-of-the-art car and advanced concept train car and subsystems are under design. These designs involve many factors of which noise and vibration control are but one. TSC noise personnel have met with the Boeing representatives and discussed the noise specification criteria and appear likely to remain involved in this technical area as the project proceeds. Several transit properties in their list of needs have mentioned the "quiet car" concept. If the results of the state-of-the-art survey show the feasibility of this goal, then our familiarity with the Boeing designs will serve as a starting point for further advances in rapid transit car noise and vibration control.

Continued liaison with the transit industry will take place through the distribution of interim and final reports on the demonstration projects planned. It is expected that the design details and specifications resulting from these demonstrations will fill the information gap in the transit industry on how to proceed with the solution of their most urgent noise and vibration problems.

SCHEDULING

This program combines in the first phase, design and implementation in the field of the wheel squeal demonstration and the state-of-the-art survey information gathering effort needed for the later demonstrations. Therefore, the scheduling can be firm only in the first year. Schedules of work on later demonstrations will require more technical information and consultation with the properties to arrive at final decisions on site location and timing. The nature of these demonstrations such as station and tunnel acoustics, floating slab design and construction, sound and vibration barriers, elevated structure noise and vibration reduction, yard noise suppression and improvements in joints, fasteners, pads and special track work require careful coordination with the operating schedules and internal plans of the properties. These scheduling plans will be announced when all the facts are in.

The planned distribution of funds for Fiscal Year 72 by technical area is:

1. State of Art Survey — $70K
2. Wheel Squeal Reduction: — $120K

   Resilient wheels
   Damped wheels
   Lubricant & resilient rails
   Wheel Squeal Consultation with Transit Properties

3. Preliminary planning of Two Demonstrations — 10K

In Fiscal Year 1973 the State of Art Survey will be continued to completion and reports issued. Planning work will begin on additional demonstrations using this information. The total funding for this phase is estimated at $910K. Interim demonstrations may be achieved during Fiscal Year 1973.

In Fiscal 1974 the effort will be devoted to demonstrations with an allocation of $1,200K. To complete the demonstrations, conduct tests, collect and analyze data and distribute reports in Fiscal 1975 the estimated requirement is $750K. On the following page is a chart (Figure 1) showing the organization of work in the first phase (FY 72, and the first half of FY 73). Figure 2 is a preliminary schedule for the total program.

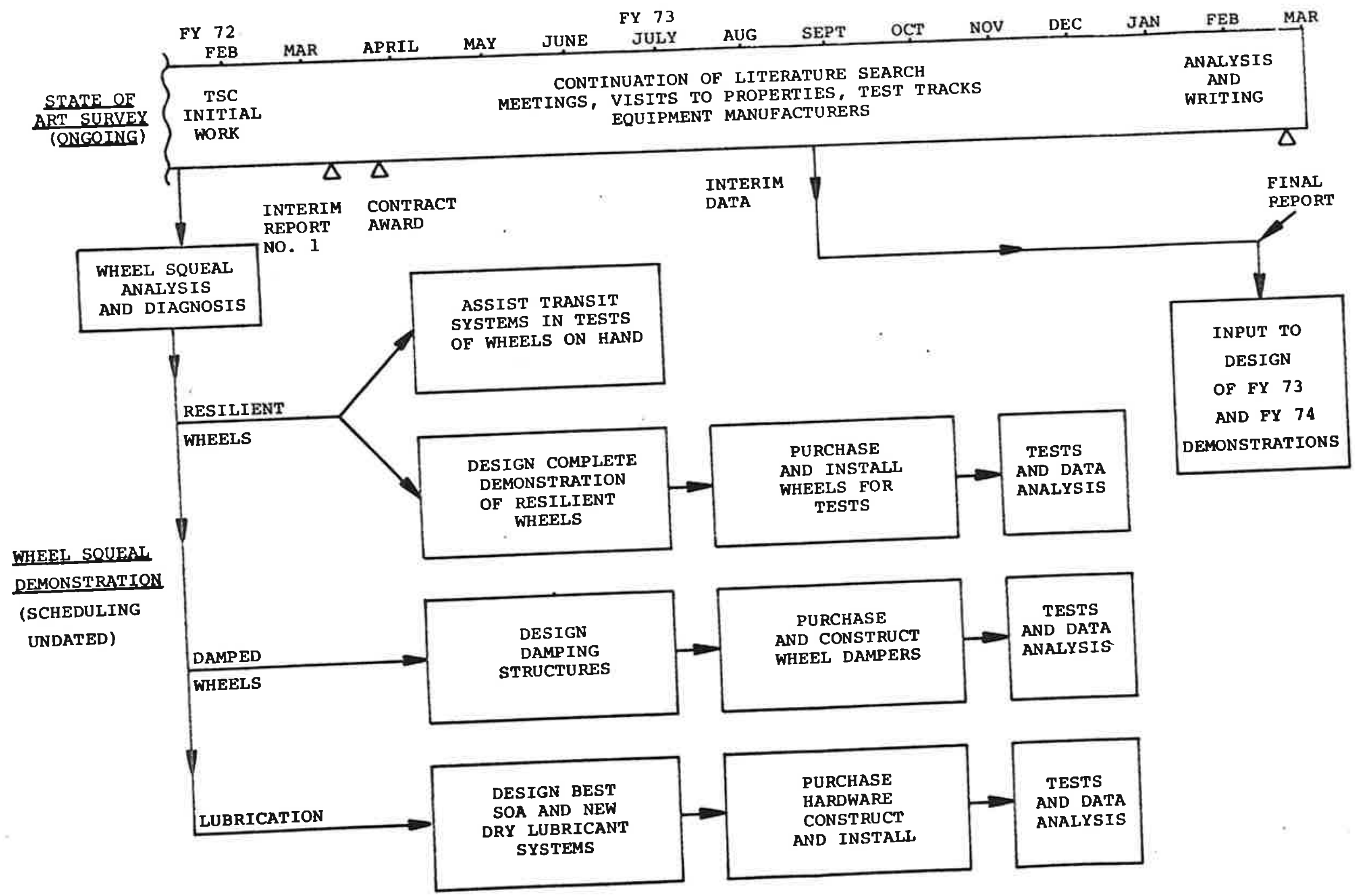

Figure 1. Schedule Chart for First Phase of Rapid Transit Noise Abatement Program

TASK	FY 72	FY 73	FY 74	FY 75
STATE OF ART SURVEY	INITIATE 3/72, $70K, CONTRACT 4/72	COMPLETE, REPORT, $70K	UPDATE REPORT	UPDATE REPORT
WHEEL SQUEAL	CONTRACTS: INITIATE 3/72, $120K, INTERIM REPORT 6/72	INTERIM DEMONSTRATION, $170K	INTERIM REPORT, DEMON-STRATION	DATA ANALYSIS, COMPLETE, REPORT
CONCRETE FLOATING SLAB	INITIATE PLANNING 4/72, $5K	CONTRACT, $250K, INTERIM REPORT	COMPLETE CONSTRUCTION	DATA ANALYSIS, REPORT
WAYSIDE SOUND AND VIBRATION BARRIERS		INITIATE, $45K	INTERIM REPORT, COMPLETE CONSTRUCTION	DATA ANALYSIS, REPORT
ELEVATED STRUCTURE IMPROVEMENTS		INITIATE, $40K	INTERIM REPORT	COMPLETE, REPORT
STATION AND TUNNEL ACOUSTICS	INITIATE PLANNING, $5K	CONTRACT, $160K, INTERIM REPORT	INTERIM DEMONSTRATION	DEMON-STRATION, COMPLETE, REPORT
RAIL JOINTS AND FASTENINGS		INITIATE, $50K	INTERIM REPORT	COMPLETE, REPORT
YARD NOISE ABATEMENT		INITIATE, $50K	INTERIM REPORT	COMPLETE, REPORT
ADDITIONAL TASKS BASED ON SOA SURVEY		INITIATE, $75K		
COST TOTALS	$200K	$910K	$1.2M (PRELIMINARY)	$750K (PRELIMINARY

Figure 2. Preliminary Time-Cost Scheduling

TSC CAPABILITIES IN NOISE CONTROL

NOISE CONTROL PROGRAMS AT TSC

Since its beginning on 1 July 1970, TSC has had an active Transportation Noise Abatement program. Under the sponsorship of the Office of Noise Abatement, Office of the Secretary of Transportation, TSC has actively engaged in the areas of field measurement of vehicle and community noise characteristics, computer simulation of noise exposure levels around airports, highways, and railways, sponsorship of basic research projects in noise generation mechanisms, and general technical support OST, FHWA, FRA, and UMTA programs related to noise abatement aspects. As a result of this program, TSC has a group of scientists, engineers, and technicians intimately familiar with noise problems. These individuals are available to participate in the proposed Rapid Transit System Noise Abatement program:

Personnel -

John E. Wesler, currently Task Manager for the Transportation Noise Abatement program at TSC, with graduate education in Acoustics and considerable experience in noise propagation and control problems;

Dr. Edward Apgar, graduate training in physics, recent experience in ultrasonics and training in transportation noise abatement, is actively engaged in a survey of the state-of-the art in rapid transit noise control through discussions with transit authorities, literature reviews, and analyses of specific problem areas.

Dr. Robert Lotz, recent graduate training in transportation noise and vibration fields, now actively engaged in development of advanced technology programs at TSC in rail transportation;

Edward Rickley, an Electronics Engineer, responsible for design and operation of the TSC mobile noise vans, and actively engaged in field measurements of transportation noises;

Robert Mason, a Mechanical Engineer, recently managed an extensive noise measurement survey and analysis program at TSC to survey the noise characteristics of Medford, Massachusetts, and presently supporting the FHWA in developing noise standards and noise prediction procedures for compatible land use near highways;

Three technicians, expert in field measurements of transportation noise levels, and laboratory analysis of those measurements, including recent measurements and analyses of subway car noises in the New York City Transit Authority and the High Speed Ground Test Center at Pueblo, Colorado.

APPENDIX A

Compilation of Known Data on Noise Sources, Mechanisms and Proposed Solutions, Tables A-1, 2 and 3.

TABLE A-1. SOURCES, MECHANISMS AND SOLUTIONS FOR RAIL TRANSIT NOISE WHEEL SQUEAL

Source	Mechanism	Solutions
1. Common Wheel Squeal	Oscillation of one of several natural modes of vibration of a wheel driven by the non-linear stick slip effect.	a) Theoretical: Beter analysis of wheel vibration modes and effectiveness of resilient wheels and damping techniques. b) Experimental: Test resilient wheels, damped wheels, lubrication, and resilient track surfaces.
2. Flange Rubbing	Same as above.	Same techniques as above in addition to special hardware to minimize flange rubbing effects.
3. "Acceleration" Squeal (Cleveland System)	Unknown.	Determine by experimental and analytic studies.
4. Retarder Yard Noise	Oscillations of wheels and retarder plates.	Change to ductile iron or non-metallic material. Self-lubrication using porous, sintered, plates.

TABLE A-2. LOW FREQUENCY WHEEL-RAIL NOISE

Source	Mechanism	Solutions
1. Wheel Flats	Skidding on track by excessive brake torque on one or more wheels.	Improved inspection, detection and maintenance procedures. Non-skid brake system.
2. Wheel Roughness	Corrosion, random wear on track irregularities.	Regular inspection, grinding.
3. Track Roughness	New track scale and rust. Uneven the supports. Loose bolts, pads. Excessive acceleration causing "wheel burn". Corrugated track-cause not understood. Bolted joints with loose components.	Regular inspection, grinding. Nonskid acceleration systems "Corrugation" phenomenon needs further study. (Flexible track supports seem to minimize effect). Welded rails, adhesive assisted bolted joints.

TABLE A-3. PROPULSION SYSTEM AND AUXILIARY EQUIPMENT

Source	Mechanism	Solutions
1. Gear Noise	Torque converting gears produce ringing noise at certain frequencies.	Better design of gear system. Better sound insulation around gear boxes.
2. Motor Noise	Needs study. Is related to ventilation. Non-uniform acceleration contributes.	Analysis of mechanisms needed. Comparison of forced ventilation vs self-ventilation systems effectiveness with speed.
3. Power Pickup Noise	Make and break contact with power rail. Use of worn running rail for power rail.	Improved design of power pickup system. Use lighter weight, low friction contact, electromagnetic feed-back forces to preserve rail contact at rough spots.
4. Loose Structural Components	Resonant vibration and rattle of loose components.	Tighter construction. Use of more welding in place of bolts, or rivets. Elimination of all loose chains and components not rigidly connected.
5. Generators 6. Compressors 7. Ventilation Systems 8. Door Closing Mechanisms	Airborne noises and resonant structural vibrations in car body components such as walls, windows, floors.	Application of state-of-the-art good practice in acoustic design for noise and vibration abatement for machinery and housings.

APPENDIX B

State-of-the-Art Survey Requirements

The information search carried out for the preparation of this proposal although limited in depth has established a number of areas where demonstrations of improved noise and vibration control features needed and where existing technology makes demonstrations feasible. However, considerable more information on needs and means is required for the detailed designs necessary. This additional information will come from (1) further analysis and follow-up on the results of the UMTA/TSC questionnaire (2) more thorough literature search of published reports and contracted studies on vibration, acoustics, rapid transit hardware and their combinations (3) meetings and communications with informed individuals in the transit industry (4) visits to particular transit systems and equipment manufacturers and (5) field measurements of noise and vibration data where required.

The state of art survey will cover all the important aspects of noise abatement in rapid transit systems, but some areas which even at this early stage clearly deserve study are as follows:

1. a. Descriptions of existing systems, changes in progress and systems under construction.
   b. Systems under design or in the early planning stages. (Determine the status of and techniques of vibration and control.)
   c. Study the United States systems from the viewpoint of needs for improvement and look into Canadian, European, and Japanese systems for information on successful technology for application in the United States systems. Examples are the Berlin, Hamburg, Paris, and Tokaido systems, which are among the quietest and most advanced in the world.[5]

2. A survey of conventional and novel types of sound absorbing materials is needed with the goal of selecting the types best suited for the many requirements of the rapid transit industry. The characteristics and costs of the following should be looked into: fiber glass, foam plastic, lead septum sandwich types, waterproof coated types, rubber[6] cork, asbestos, porous concrete (Celotex, sawdust, wood chips). Materials for special requirements should be evaluated, such as for use in (1) car construction (spray or foam plastic or fiber glass in car walls) (2) station and tunnel walls (require durability, washability) (3) station ceilings (non-dust catching, light reflecting) (4) under the platform (non-dust catching, fireproof, durable) (5) track invert (resilient, fireproof, durable).

3. Compare various rail joint types such as: welded (gas heated, electrical, thermit), adhesive[7] and bolted types. Determine costs, reliability, maintenance, noisiness, change-over feasibility on existing systems and possibilities for new or improved techniques and hardware.
4. Study whole area of brakes, acceleration control, optimum speed control, and non skid systems with a view towards passenger comfort, equipment maintenance, thermal effects on wheel materials, prevention of wheel flats, rail wear, and corrugations. Define optimum control system from noise abatement viewpoint.
5. Rail-Wheel maintenance procedures: study current methods, equipment and scheduling to arrive at specifications for optimum maintenance technique. Consider feasibility of designing a standardized rail grinding and polishing car equipped with sensors for measurement and diagnosis. Also, standardized wheel grinding and polishing equipment to minimize down time.
6. Wherever appropriate, look at noise and vibration control in relation to other factors from the "systems" viewpoint. Consider trade-offs and cost effectiveness (Example: brake system design which involves safety and passenger comfort also).
7. Examine municipal noise codes and their relation to noise level specifications in the rapid transit industry. Compile some realistic figures for noise levels possible on well engineered system.
8. Organize the output of this state-of-the-art survey in a form which will be of maximum use to the transit industry in planning and designing new equipment.
9. Site selection for demonstrations.

APPENDIX C

Wheel Squeal Reduction Demonstration Project

The goal is to implement under actual service conditions each of the several most promising methods for reducing the high frequency pure tones in the wheel/rail interaction spectrum. This noise, in the 600 Hz to 3000 Hz range, is produced by wheel oscillations in a resonant mode driven by non-linear stick-slip friction forces. Because of its intensity, its frequency (in the range of maximum sensitivity of the human ear) and its prevalence on the majority of transit systems this particular problem has a high priority in our abatement program. Useful work can begin nearly immediately because of the state of understanding of the source mechanism and the number of different abatement techniques which have contributed to the progress in the search for the most effective solution. These include resilient wheels, wheel damping, lubrication, and use of a resilient tread on the rail surface. Each method examined, however, has unique advantages and disadvantages, so that a methodical, quantitative comparison is needed before a particular solution can be recommended as best on United States rapid transit systems.

Analysis of the wheel oscillation phenomenon has led to insight into the mechanisms[8]. The stick-slip friction force excites a number of wheel vibration modes, of which the in plane mode is most efficient for sound radiation. The lowest elastic frequency mode determines the fundamental frequency of the radiated sound. Further work of this nature will be helpful at arriving at wheel designs or choice of materials to reduce wheel squeal at the source. In parallel with such theoretical work with a long term pay-off, a number of known techniques based on a rough understanding of the effect will be tested and where possible optimized for a more immediate application.

One method, experimented with and tested for many years and recently gaining in success, uses a wheel which includes a non-metallic resilient structure. Several varieties exist, including the Acousta Flex[9] wheel (also called the B-L-H or Baldwin-Lima-Hamilton type), the S A B wheel of Swedish make[10] and the Penn Machine Company Resilient Wheel (developed in Europe by the Bochumer Verein A. G.)[11]. The latter type have been used on certain European railroads for long periods with apparent success. Small numbers have been tested in the United States with good results without widespread adaption. One disadvantage is high cost, although the claim is made that in the long run the advantages of fewer wheel flats and reduced equipment maintenance offsets the initial cost. In the near future, a number will be tested on a Green Line street car of the Boston MBTA line. This line has tunnels, sharp curves, grade level sections and steel elevated structures so the test will provide a quantity of useful data. If these wheels reduce the noise and vibration and also fulfill other requirements,

the chance of wider adaptation is good. TSC will provide temporary assistance in making measurements in these tests to insure the collection of meaningful data "before and after" noise and vibration with the wheels. Extended data collection and analysis over a long period in order to take advantage of this opportunity to observe resilient wheels under service conditions will be organized as a task within the scope of this proposal.

Wheel damping applied to solid steel wheels of conventional design is another promising approach. Examples are the B. F. Goodrich Company design[12] and the Soundcoat Company, Inc. processes[13]. Both are constrained layer combinations of metal-viscoelastic sandwiches attached to the wheel web. These have been tried with good prelininary success. Sound level attenuations of up to 15 dB over a wide spectrum have been reported by the best damping techniques. Some questions remain about heat resistance and long term durability which can be answered by appropriate tests and analyses. This damping method is relatively inexpensive and can be adapted to existing wheels, with very short down-times, making it an attractive short term solution.

Rail lubrication on rapid transit systems is a fairly common practice although the type of process varies widely. These include grease applicators, fog spray, and a kerosene-soaked wick in a slot on the tangent track preceding a curve[14]. The common concern in wet lubricant systems is the prevention of lubrication of the rail head running surface with the consequent loss of adhesion, wheel-rail slippage, and wheel flat development. Also, accumulation of greasy residue can be a problem. The development of efficient dry lubricant techniques in other fields suggests the possibility of applying a long lasting solid lubricant section in such a way as to eliminate flange rubbing induced squeal. Materials such as wire-filled compressed carbon, filled teflon or molybdenum disulphide are obvious candidates and several hardware designs are promising enough to require more detailed study and tests under this program.

An alternative to resilient or damped wheels and lubricated track is the technique of applying a layer of resilient tread on the track surface. The CTA system made tests of rails covered with a 1 1/4 in. layer of polyurethane elastomer provided by the Goodyear Tire and Rubber Company. A modified rail (wider head, machined flat) had the elastomer "vulcanized" on the surface by a factory process [15]. This elastomer, extremely wear-resistant, is the same material as used in truck fork lift tires and has approximately eight times the compressive strength of conventional rubber. Tests were made in the

Skokie yard for noise and adhesion under a variety of weather conditions. Some advantages claimed are equal or better adhesion than with steel on steel and a 15 dBA noise reduction. No deterioration was noticed after 2,000 car passes over a 1000 ft. section. The applicability of this technique to wheel squeal on curves is open to investigation. The usual flange rubbing and wheel skidding on curves might wear the elastomer excessively rapidly compared with wear on a tangent section. However, in recent years the quality of available elastomers of the polyurethane type and improvements in adhesives make this concept worth investigating carefully, particularly in view of its noise reduction on tangent sections in the low frequency range.

APPENDIX D

Wayside Sound and Vibration Barriers

In situations where noise and vibration cannot be eliminated by changes at the source, the next best solution is to interrupt the propagation path so the energy will be deflected or absorbed. Indoor sound barriers are useful in stations and tunnels placed alongside tracks up to a height slightly in excess of the bottom of the car, overlapping the sides. This tends to trap most of the noise and prevent it from reaching other tracks, station platforms or reverberating within the tunnel or up vent shafts to the surface. Choice of material is a problem. A good absorption coefficient across a wide frequency range is basic while economy, degree of dust collection and washability are important factors. The ideal material has yet to be discovered; different systems have tried a number of materials. Lightweight porous materials, such as fiber glass alone are inadequate. A certain amount of mass is also important, such as foam plastic with inner lead septums. The latter are likely, however, to be costly. This area of improvement requires further input from the materials section of the State of the Art Survey. Outdoor soundbarriers can be constructed of a cheaper, durable material such as reenforced earth where space is available for an embankment. This structure can be designed to deflect the sound upward. More durable and more expensive concrete and brick walls are also useful where space is limited. Absorption, instead of reflection, in trackside barriers can be achieved by choosing more porous materials such as concrete filled with wood chips, sawdust, or Celotex. Sono block, a porous concrete block with resonant cavities, is a good absorber and reasonably durable. Again, more information on materials in terms of costs and effectiveness is needed.

Earthborne vibrations to buildings are an important problem. The most common solution has been to mount the building columns on shock absorbers, an expensive and only partly effective solution. The floating concrete slab roadbed is another, more recent, solution to be discussed later. Another promising approach investigated in some detail has been isolation of structural foundations by installation of wave barriers. In theory, this can be quite effective because the Rayleigh wave, carrying 67% of the vibrational energy, travels near the surface[16]. Thus a trench or layer of soft or resilient material should interrupt the propagation. In practice, it is difficult to keep the trench open. Some economical method of preserving the gap must be discovered such as filling it with a low density durable material or structure. Various possibilities exist and must be tested under realistic conditions either on a transit property or initially at the Pueblo test site. A site where some preliminary feasibility planning for an airborne sound barrier has been done[18] is in the Wellington area of Medford, Mass. bordering the west side

of the Haymarket-North MBTA rapid transit extension. The re-enforced earth barrier proposed can be supplemented by a wave barrier providing protection against both noise and vibration for the near-by residential structures.

Finally, one of the most important applications of barriers is on elevated structures close to business and residental buildings. Theseaare now used to a limited extent and called walls or parapets. When massive enough and extending above the wheel assemblies of transit cars they are effective. The problem is to improve the technique, apply better acoustical materials (lighter weight) and install them on existing noisy elevated structures. Most systems with elevated sections are candidates for this treatment, in particular New York, Chicago, Boston, and even BARTD in one location

APPENDIX E

Concrete Floating Slab

This structure consists of a thick (up to 12 in.) re-enforced concrete slab used under a track bed in place of the usual ballast invert. Also, it is supported on a layer of resilient material which will tend to dampen vibrations of the slab. There are a number of important parameters which must be calculated (thickness of slab, mass, elasticity, resilience of supports, etc.) relative to the weight of the train. When successful, vibrations which would travel to nearby buildings are absorbed in the slab and its supports. Such slabs have been built in London and Munich and one is being considered in the new Washington, D.C. system. The New York City Transit Authority needs such slabs at certain locations and has done preliminary design work. Decisions about proceeding with construction have been delayed for financial reasons. Techniques for designing floating slabs need improvement and testing. The installation of at least one in an operational environment with a critical vibration problem, such as in New York City Transit Authority is most desirable.

APPENDIX F

Station and Tunnel Acoustics

It has long been recognized that most rapid transit underground stations and tunnels are noisy reverberant volumes in need of modern acoustical treatment. Complete treatment of a station requires use of acoustical materials on the walls, ceilings, track inverts, under the platform and in the form of barriers between the local and express tracks. Considerations of resistance to dust collection, ease of washing with water spray, durability, aesthetics, and economy must all be weighed. This challenging task is useful, however, because of the high density of exposure by patrons in stations to unusually high noise levels, sometimes exceeding 110 dBA. A material typical of today's state-of-the-art is plastic enclosed fiber glass pads protected by wire mesh for under the platform use. Traditional acoustic tiles have been installed on ceilings. Walls and track barriers are still the problem areas. Here again, information on new and better materials is essential in order to construct a model demonstration project.

A special problem exists at the entrances to some tunnels where the air turbulence effects created by an entering train produce a high transient noise level. Also the sudden increase in reverberation of wheel-rail noise adds to the effect. Acoustic analysis and modification of the tunnel portals can help reduce this problem.

APPENDIX G

Elevated Structure Improvements

Elevated structure noise, according to the questionnaire results, are next to rail-wheel noise in order of importance for noise and vibration abatement measures. In addition to wheel squeal reduction the problem is to reduce low frequency airborne noise from wheel-rail interaction and auxiliary equipment as well as structure borne vibrations into the soil. The wheel-rail and equipment (mostly propulsion unit) noise can be attenuated by improvements in track and tire pads, by sealing the track bed to prevent noise leaks into the air below and by installation of barriers (parapets) to interrupt and absorb airborne noise. A second source of airborne noise is resonant vibration of steel supported structures. Ideally, they should be enclosed in concrete using the increased mass for attenuation. In practice, the best that can be done is to (a) prevent vibrations from reaching the steel elevated structure supports by using more massive track supports (such as a modified floating slab struture where a strength permits) or (b) coat the offending steel beams with a viscoelastic damsping material[19].

The complete package of requirements for an optimum solution will depend on measurements of noise and vibration at the particular structure chosen for improvement. A good general working rule which emerges from the data examined is to design the rapid transit vehicle for minimum mass and the track bed and supporting structures for maximum mass. This fairly obvious criteria for noise reduction is not always found in proposed new transit or people-mover systems. Existing systems in urgent need of elevated structure improvement are Boston, New York City, and Chicago.

APPENDIX H

Rail Joints and Fasteners Demonstration

Another wheel-rail noise is produced by track misalignment, discontinuities at bolted joints, insulated breaks switches and special trackwork. The number of joint discontinuities can be reduced by the use of welded joints where track replacement is feasible. An investigation will be made of the state-of-the-art of field welding methods (thermite, flash butt, and gas pressure welding) to determine if a technique can be developed to quickly replace conventional bolted joints by welded ones. This will depend on the extent of damage and wear to the track ends and the stresses which the particular track-fastener installation can tolerate. Another technique to investigate is to apply an epoxy resin to bolted joints. Even though a slight rail discontinuity will remain, the resultant joint becomes a rigid unit eliminating the maintenance problem of lubricating and tightening of bolted joints. Loose, broken and inadequate fasteners will produce low frequency noise by track misalignment and excessive working of the rail under load. Also, vibration transmitted through the fastener to the roadbed will travel to nearby structures. The proper fastener design must take into account the optimum thickness and elasticity of the resilient pad. Data obtained from the State-of-the-Art Survey and other rail problem subtasks, necessary from measurements (such as on the insertion loss) will be used to make a selection of an optimum fastener design to install on a section of a transit system with a history of loose joints, defective fasteners, and maintenance problems. If possible, the demonstration will include some field welded and epoxy joints also. The section with these changes will be observed and measurements made over an extended period for comparison with old joints and fasteners given only routine maintenance.

APPENDIX I

Yard Noise Abatement Demonstration

A rapid transit system requires repair shops and special yards for holding and assembling trains. These facilities share the noise making potential of the system in general with some unique features such as coupling noises, concentrations of switches and other noisy special trackwork, and considerable braking and acceleration. Frequently, these yards are surrounded by residential and business districts whose residents are exposed to the noise on a twenty-four hour basis, unlike commuters or residents elsewhere who benefit from the slack schedule during night hours. An example is the Lenox Avenue holding yard in New York City in very close proximity to apartment houses and a school building. Here eighteen tracks converge on sharp turns into one entrance and one exit track. Residents of the area complain of the noise, especially at night. A complete study of this and several similar yards will be done to select one where the application of a number of noise abatement techniques applied to the sources and propagation paths will give significant improvement.

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