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RAPID TRANSIT NOISE ABATEMENT AND COST REQUIREMENTS (MBTA PILOT STUDY)

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L. G. Kurzweil
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16. Abstract

A methodology is described, based on a study conducted on the Massachusetts Bay Transit Authority Blue, Red and Orange Lines, to assess the acoustic noise climate of an urban rail transit system and the appropriate technology to cost - effectively reduce that climate to acceptable levels. The methodology leads to a first order assessment of abatement options and can be applied to any rapid transit property.

The methodology uses scenarios to define specific, often occuring combinations of noise at a given receiver. An algorithm is given to determine the combination of abatement techniques which will achieve a desired set of noise levels along a rapid transit line at least cost.

This report presents a pilot study of a noise level climate survey with an assessment of potential noise abatement measures. The noise climate is tabulated to permit selection of opimum cost effective techniques for abatement to the desired level. Application of the methodology to other U.S. rapid transit systems is planned.

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PREFACE

The Transportation Systems Center (TSC) is conducting a research, development and demonstration program under the Urban Mass Transportation Administration (UMTA) Office of Research, Development and Demonstration Rail System Supporting Technology Program. The TSC effort is directed towards reduction of acoustic noise in urban rail systems, thereby contributing to improved environmental quality for users and the community. The program will make available, in a form useable in present and planned urban rail systems, the technology for control of acoustic noise and will provide UMTA with the tools required to evaluate and recommend noise abatement measures for urban rail systems.

Initially this effort is being directed towards an assessment of the current acoustic noise climate of urban rail systems and the technology available for reducing this climate to acceptable levels. In order to establish and demonstrate the methodology for conducting this assessment a pilot study of the Massachusetts Bay Transit Authority (MBTA) rapid transit system was conducted.

The assessment of the noise climate and state-of-the-art of abatement technology will provide:

- Dollar estimates of capital and maintenance costs for applying proposed noise control standards to operating properties,
- Site specific definitions of noise abatement requirements, for guideline use all for all existing urban rapid rail properties, and
- Identification of requirements for new and approved technology.

An additional function of the MBTA pilot study has been to identify gaps in the methodology for assessment of rail system noise climates and current abatement technology. It is hoped that

this report will serve as a focus for constructive criticism and recommendations for improvement of the assessment methodology.

In addition to the authors, the following individuals of the Noise Abatement Group, Transportation Systems Center, contributed to the data in this report: E. J. Rickley, R. W. Quinn, and N Sussan. Dr. H. Weinstock offered numerous suggestions which substantially contributed to the formulation of the methodology described in Section 3. The efforts of F.J. Rutyna of the TSC Urban Rail Program Office, in coordinating the activities of the Noise Abatement Program (UM304) are also acknowledged.

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1. SUMMARY

Noise generated by urban rail rapid transit systems is becoming increasingly less acceptable as the public demands higher standards of environmental quality. As noise abatement emerges as an issue, a number of engineering as well as socio-economic and political questions become relevant. This report is primarily concerned with the engineering aspects of noise (Questions (1) - (4) below) but also considers some of the socio-economic aspects involved (Questions (4) and (5)). Question (6) below is not addressed in this report. It is posed, however, in order to emphasize the importance of, as well as some of the constraint on, Question (5) - desirable or required noise goals.

The following questions are consider relevant:

(1) How much noise are different individuals patrons, employees, neighbors) exposed to in and around each rapid transit system?

(2) What noise sources and propagation paths are responsible for the noise climates?

(3) What noise abatement techniques and components are presently available?

(4) What are the capital and maintenance costs of noise abatement as a function of abatement goals and what is the minimum cost for a given goal?

(5) What noise limits and associated abatement goals are desirable or might be required by new regulations?

(6) Who should initiate noise abatement, what implementation schedule is appropriate and who should bear the cost?

Questions (1) to (4), dealing with noise exposure, sources, available abatement techniques and cost, are straightforward engineering questions with straightforward engineering answers. No institutional issues are involved and the uncertainity of the results may be made arbitrarily small, depending on the applied level of

effort. Questions (5) and (6) dealing with desirable or required noise limits, and with responsibilities for implementation are more complex and difficult to answer in view of the socio-economic issues involved.

Section 4 of this report provides a brief review of material relevant to the answering of Question (5). This review considers the work of such agencies as the U.S Environmental Protection Agency, the U.S. Department of Housing and Urban Development, and the Institute for Rapid Transit.* Essentially, there are neither current nor projected laws, regulations or any standards which set limits to the noise generated in and around operational urban rapid transit systems. Instead, there is a variety of suggestions, recommendations, and guidelines, available mainly for discretionary compliance.

The answers to questions (1) - (4), presented in Section 2 and Section 3, are believed to be adequate for all engineering tasks preceeding the implementation stage of noise abatement.

An approach to answering Question (1), noise exposure, is illustrated in the MBTA example in Section 2. Included in this Section are descriptions of the general system layout, operational data, and existing noise climates for all relevant receivers: in-car riders, people in stations, and the wayside communities. Noise measurements and other relevant data have been reduced, analysed and summarized in several tables and charts.

Generally speaking, the following ranges of noise levels exist:

- In-Car 70 to 95 dBA
- In-Station 80 to 95 dBA
- Wayside (at 50 ft) 80 to 95 dBA

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* See References 15 - 17, Appendix C.

The ranges found in the MBTA generally correspond with typical noise ranges for U.S. rapid transit systems.* Singularities such as wheel squeal may increase the above limits by as much as 10 dBA.

Section 2 also combines acoustically similar segments of each rapid transit line into noise control classes. This is the first step in the methodology developed in this report for dealing with Questions (2) to (4), sources of noise, abatement techniques and cost. The other steps of the methodology, developed in Section 3 and Appendix A, include:

- Identification of contributions made to each noise class by each noise source via each major noise path,
- A compilation of rapid transit noise reduction techniques and components; their approximate costs and their effect on noise sources and paths
- An algorithm for determining the combination of noise abatement techniques for individual line segments and rail cars, which will result in meeting a specified noise abatement goal, at a minimum total cost.

In the pilot application described in this report, this methodology has been applied to three rapid transit lines of the MBTA. The detailed results are presented in Section 3 and are summarized in Figure 1.1. This figure presents the cost (including material and labor but not engineering costs.) of abatement (using least-cost strategies) versus a specified upper limit of noise on the three MBTA rapid transit lines. Results are given for each class of receiver individually as well as for all receivers simultaneously. The sound pressure (noise) measurements appear in dBA units; a unit compatible with actual human response.

The base costs appearing in Figure 1.1 are necessary for eliminating the noise singularities (wheel squeal, track geometry

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* See Ref 15, Appendix C

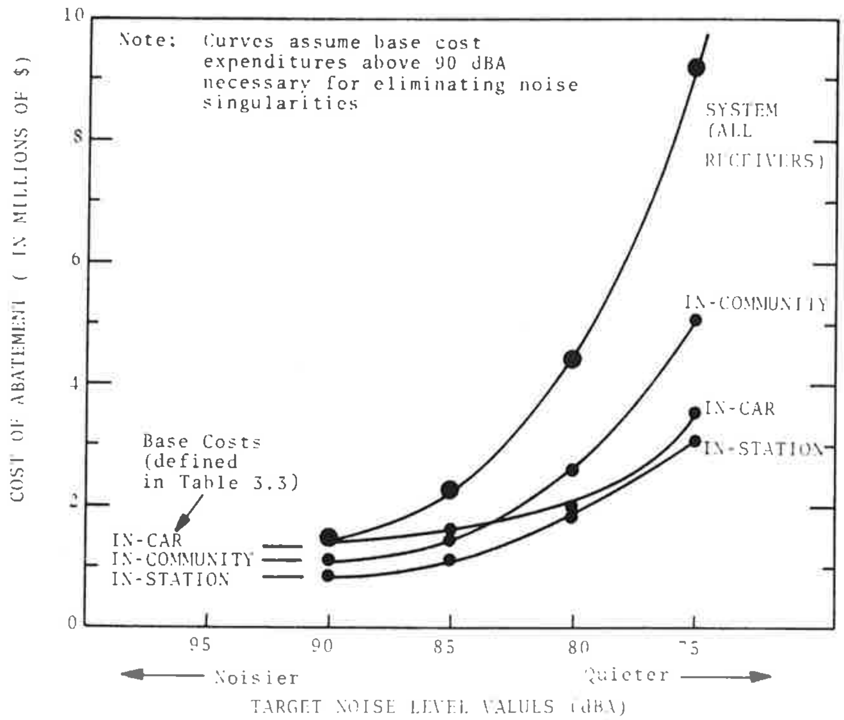


Figure 1.1 Cost of Abating the MBTA Rapid Transit System to a specified Level (dBA) at Each Receiver

problems, air brake vents, and noisy doors.) present in the system. Figure 1.1 shows abatement costs accelerate very rapidly as a quieter system is specified primarily because an increasingly larger fraction of the system requires noise abatement treatment.

Figure 1.2 presents the picture differently. In this plot costs have been normalized for a unit track length in feet, and a unit of noise reduction (dBA). The cost, in dollars per foot of double track per dBA, is seen to be relatively insensitive to either the specified noise limit or to the portion of the system requiring abatement. Figure 1.2 shows that the normalized abatement cost is approximately $2.50, $5.00 and $10.00 per linear foot of double track, per dBA, for noise abatement in car interiors, in the wayside community and in stations respectively. (These are very rough numbers for purposes of engineering estimates. Engineering costs as well as the base costs identified in Figure 1.1 are excluded.)

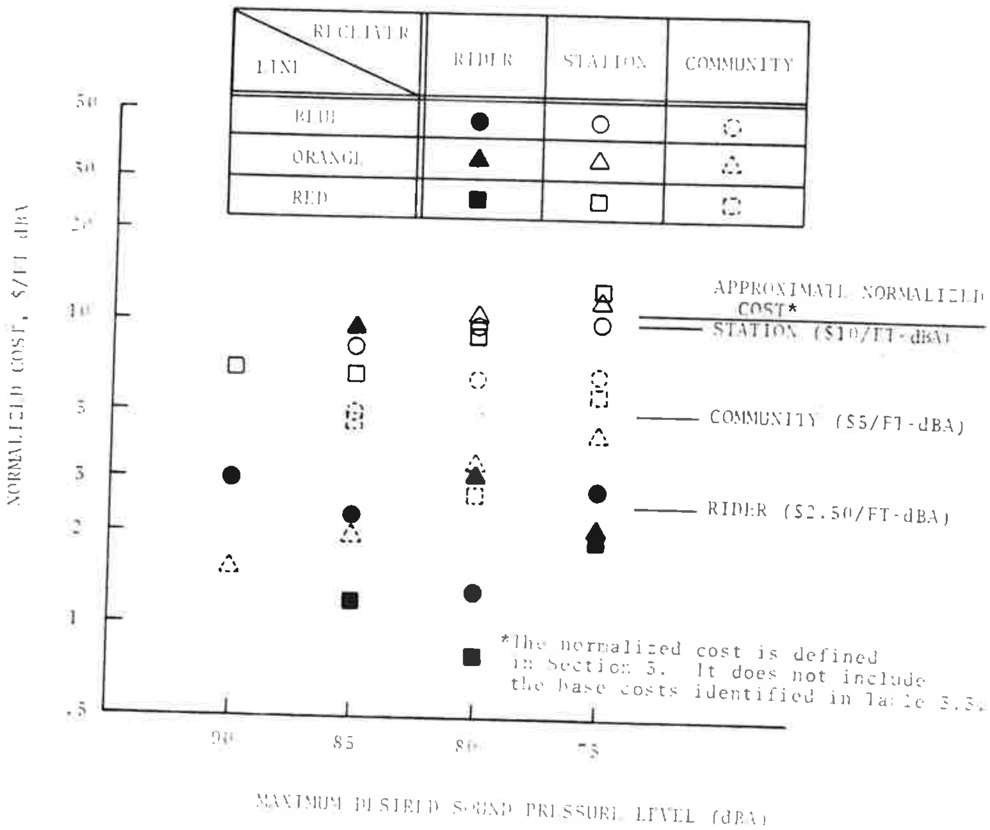


Figure 1.2 Dependence of Normalized Cost on Desired Abatement Level

It should be noted that in Figure 1.1 no calculations have been carried out for abatement below 75 dBA. The reason is that the effectiveness of the analysis diminishes rapidly below this level.

Although the specific treatment of problems addressed in this report is peculiar to the MBTA, the approach is intended to be general and is applicable to all rapid transit systems. The primary contribution of this report is thus the methodology for defining the rapid transit noise climate and obtaining least-cost abatement strategies.

2. MBTA NOISE CLIMATE

2.1 BACKGROUND AND GENERAL DESCRIPTION

The Massachusetts Bay Transit Authority Rail Transit System comprises three lines, color coded as the Blue Line, the Orange Line and Red Line. The route structure is shown in Figure 2.1.

The Blue Line is six miles long and has twelve stations. The first two miles and the first five stations (from Bowdoin to just beyond Maverick) are underground. The remaining four miles to the terminus at Wonderland are at grade level. Running time is eighteen minutes. About 2 1/4 miles at grade level are adjacent to residential areas. Twenty-four cars of the 75 car fleet are about 35 years old and are scheduled for replacement within the next few years. The remaining cars are about 20 years old. None of the cars is airconditioned.

The Orange Line has 8.5 miles of double track and fifteen stations. Starting from Everett, the line runs on an elevated structure for 3.8 miles (five stations) to North Station. From there it enters a 1.2 mile tunnel with four underground stations to Essex Station. Beyond, the line emerges and continues on an elevated structure through six more stations to Forest Hills. About four miles of the elevated line are adjacent to residences and commercial buildings. One hundred cars are used for this line. The running time is about 30 minutes.

The Red Line comprises underground and grade level sections. The original line, referred to as the Ashmont Branch, is 9.0 miles long with a 25 minute running time covering the 14 stations between Harvard and Ashmont Stations. Beginning from Harvard Station the line runs underground for three stations (2.3 miles) to Kendall. Charles St. Station and the adjacent track is elevated; after this, the next five stations to Andrew are underground. Emerging to grade level after Andrew this line continues through five stations (3.4 miles) to Ashmont. The new South Shore Extension covers 6 1/4 miles (3 stations) of grade level track between

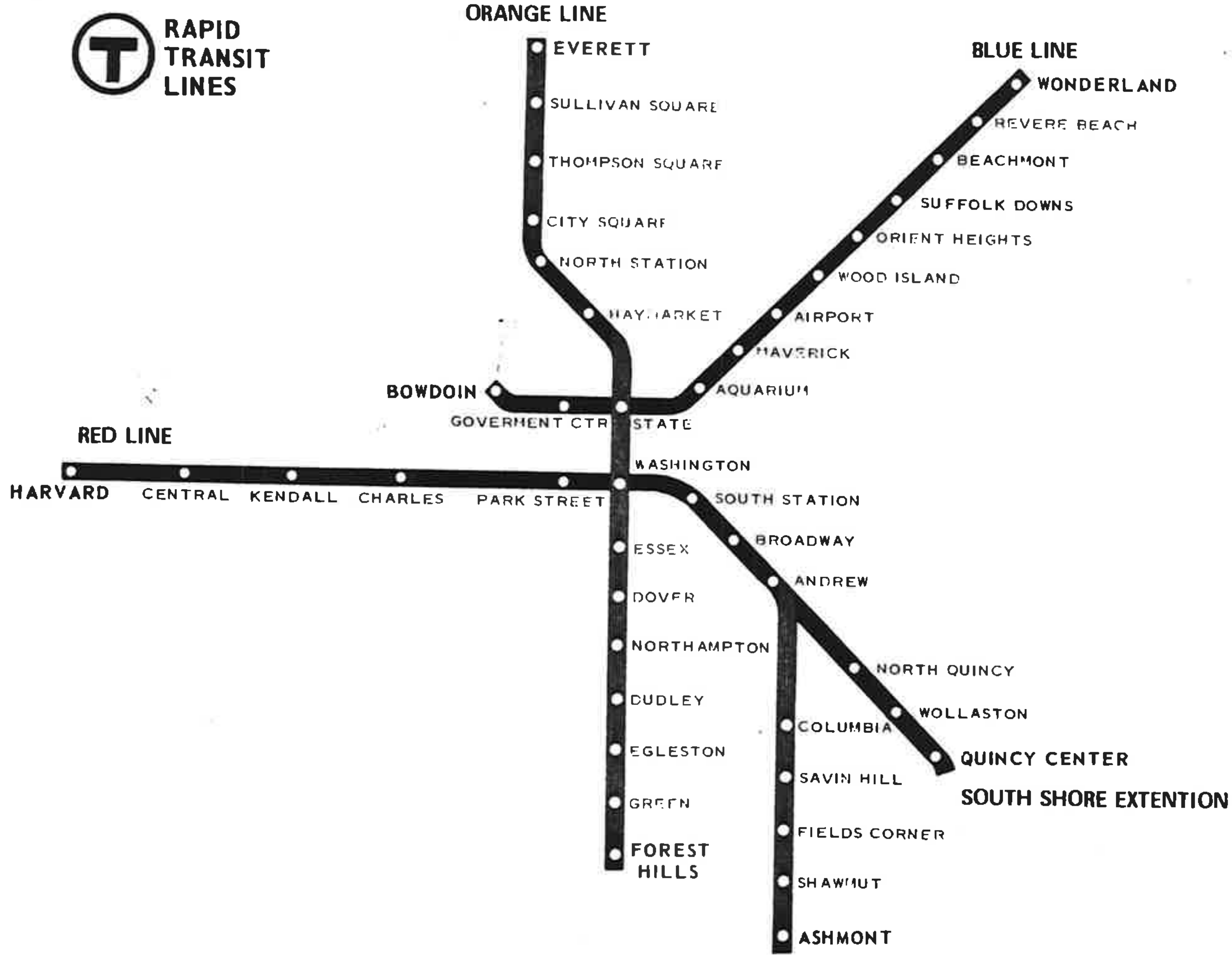


Figure 2.1 MBTA Rapid Transit Lines - Schematic

Andrew and Quincy Center. The Ashmont line has about 1 1/2 miles of interface with residential neighborhoods while the South Shore Extension has three miles of residential interface. The line has a total of 168 cars. Of these, 92 are older cars built in 1963 and called "Bluebirds" by the Authority because of their blue painted exterior. These run only on the Ashmont branch during normal operation. The remaining 76 cars were acquired about 1970. These "Silverbirds" (so called because of the brushed aluminum exterior finish) are air conditioned and capable of 80 mph. operation. Silverbirds ordinarily operate between Harvard and Quincy Center stations.

Except for the South Shore Extension of the Red Line, most of the at grade and underground track on the rest of the system is of jointed rail, wood tie, on stone ballast construction. Most elevated track is of jointed rail, with wood ties directly attached to the structual steel frame. The South Shore Extension is entirely of welded rail, concrete tie and stone ballast construction.

2.2 NOISE MEASUREMENT DATA

This study encompassed measurements of in-car, in-station and nearby community noise. Overal summary data is shown in Figures 2.6 and 2.7 at the end of this section.

2.2.1 In-Car Noise

Continuous recordings of the in-car noise levels were made for one round trip on each rapid transit line.

Figure 2.2 shows a sample time history of the dBA noise levels experienced by the rider on the train both in and between stations. It can be seen that as the train leaves the station and accelerates, the noise level increases. The level reaches a relatively constant "plateau" while the vehicle maintains a constant speed and finally decreases as the train pulls into the next station.

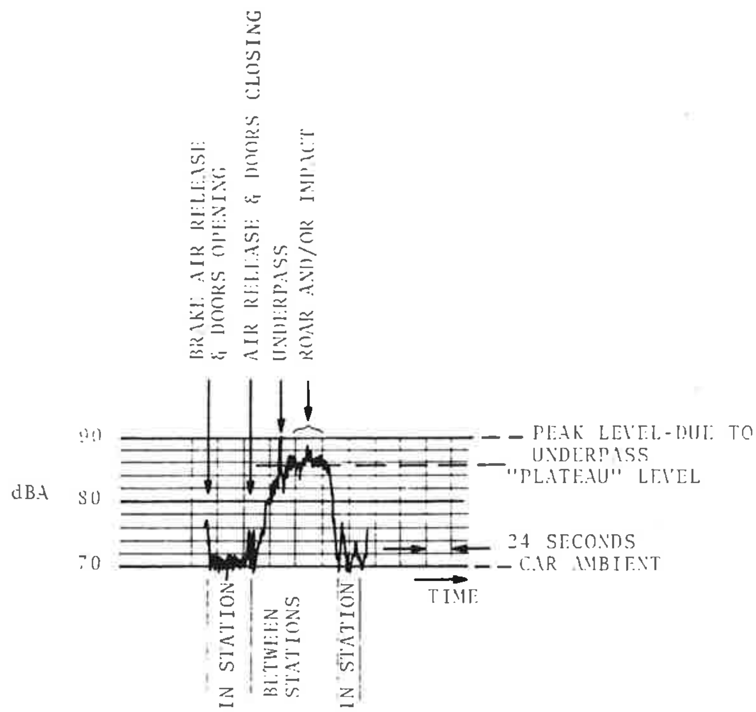


Figure 2.2 Sample Time History of In-Car Noise Levels (dBA)

The recorded data for each line have been divided into a series of plateau values for the rides between stations. In cases where the ride between stations included more than one type of line construction; e.g., tunnel and at-grade, a plateau level for each segment is given. The results are shown in Table 2-1 and are further summarized in Figure 2.7 at the end of this section. Figure 2.7 also defines the track sections of Table 2-1 which groups lengths of track having similar noise sources, paths and levels and gives the total track length in each category.

Since certain combinations of noise sources and paths contribute to the noise at a given receiver, it is useful and convenient to define scenarios, which are specific, often-occuring combinations. The noise level at each receiver depends on many factors, e.g., vehicle type and speed, track type, (jointed or welded, tie on ballast or direct fixation to concrete invert) and track construction (subway, at-grade, or elevated). At any

TABLE 2-1 LINE SUMMARIES FOR IN-CAR NOISE

BLUE LINE

TRACK TYPE	95 dBA[a] LENGTH (ft)	95 dBA TRACK SECTIONS	95 dBA SCENARIO #	90 dBA LENGTH (ft)	90 dBA TRACK SECTIONS	90 dBA SCENARIO #	85 dBA LENGTH (ft)	85 dBA TRACK SECTIONS	85 dBA SCENARIO #
TUNNEL	4,780	6a,4	R1	2,770	5	R2	2,460	1,2,3	R3
UNDERPASS	180	7a,10a 11a	R1	120	8a,10b	R2	-	-	
AT-GRADE	-	-	-	-	-	-	17,550	6b,6c,7b, 7c,8b,8c 9a,9b, 10c,10d 10e, 11[illegible]	R3

ORANGE LINE[b]

TRACK TYPE	90 dBA (a) LENGTH (ft)	90 dBA TRACK SECTIONS	90 dBA SCENARIO #	85 dBA LENGTH (ft)	85 dBA TRACK SECTIONS	85 dBA SCENARIO #	80 dBA LENGTH (ft)	80 dBA TRACK SECTIONS	80 dBA SCENARIO #
TUNNEL	190	5b	R2	140	6,8	R3	840	7,9a	R4
ELEVATED	-	-	-	8,710	12b,14a, 14b	R7	21,240	1,2,3,9b, 10a,10b, 11a, 11b, 13	R5

RED LINE (ASHMONT)[c]

TRACK TYPE	90 dBA LENGTH (ft)	90 dBA TRACK SECTIONS	90 dBA SCENARIO #	85 dBA LENGTH (ft)	85 dBA TRACK SECTIONS	85 dBA SCENARIO #	80 dBA LENGTH (ft)	80 dBA TRACK SECTIONS	80 dBA SCENARIO #
TUNNEL	15,780	1,2,7b,8	R2	11,100	3a,4b,5 6,7a,12b 13	R3	1,760	9a	R4
AT-GRADE	-	-	-	2,290	11a	R5	6,640	9b,9c, 10b,12a	R6
ELEVATED (& BRIDGE)	-	-	-	-	-	-	2,340	3b,4a	R6

RED LINE (SOUTH SHORE EXTENSION)

TRACK TYPE	80 dBA LENGTH (ft)	80 dBA TRACK SECTIONS	80 dBA SCENARIO #	75 dBA LENGTH (ft)	75 dBA TRACK SECTIONS	75 dBA SCENARIO #	70 dBA LENGTH (ft)	70 dBA TRACK SECTIONS	70 dBA SCENARIO #
TUNNEL	-	-	-	1,960	9a	(d)	-	-	(d)
AT-GRADE	-	-	-	-		-	28,540	14a,14b, 14d,14e, 14f, 14h, 15a,15b	

(a) Levels indicate center dBA value for 5 dBA range

(b) In addition to the track sections given in the chart, elevated sections 4, 5a and 12a account for 4550 ft at 75 dBA.

(c) There are 2640 ft of at-grade track (section 11b) not included in the chart. The plateau level on this section is 77 dBA.

(d) No scenarios were defined for levels below 78 dBA.

Refer to Figure 2.7 for locations of all track sections.

location along the track the noise level at a given receiver is a combination of noise from several sources transmitted via several paths. For this report sections of track with acoustically similar characteristics were grouped together into noise classes on the basis of a) recorded noise data, b) notes taken on a rapid transit line including truck construction, rail condition, grade and curve, station construction, etc, and c) engineering drawings. For each noise class, a scenario was defined which identified the contribution of each source-path combination to the overall noise level at each receiver. Ideally, diagnostic experiments should be performed to quantify the primary source-path contributions. For this report, however, diagnostic data from previous field studies (BART, Toronto, etc.) were used in conjunction with the data indicated above to formulate the scenarios. Although this is adequate for the first order estimate obtained in this study, the more important details of the scenarios should be verified through experiments before the engineering of actual noise abatement is carried out.

Definitions of scenarious used for the MBTA cost abatement analysis are given in Appendix B. Table 2-2 shows a sample scenario for in-car noise and is representative of other types of scenarios prepared for in-station and wayside noise analyses.

The information presented in the figures and tables referenced above does not include noise singularities such as wheel squeal or excessive hunting. This data is summarized in Figure 2.3 which indicates the squeal, hunting and underpass locations; in addition, the average of the peak dBA levels for two passes is given at each of these locations.

2.2.2 Station Noise

Platform noise level measurements were made in eighteen of the forty-four stations of the three rapid transit lines. In some cases continuous recordings were made and in others a series of rapid hand held meter readings were obtained. The microphone

TABLE 2-2 SAMPLE SCENARIO FOR IN-CAR NOISE

Scenario Number (Total level dBA)	Verbal Description: Track	Verbal Description: Car
R1 (95 dBA)	tunnel; jointed rail; wood tie on stone ballast, rough rail surface	rough wheels, no wheel flats, car poorly sealed, mechanical and auxiliary noise typical of older car

Acoustic Description

Paths:

- Pa: structure borne
- Pb: interior reverb.
- Pc: exterior reverb.
- Pd: car transmission loss
- Pe: direct field exterior
- Pf: direct field interior

Estimated Path Contribution	Paths	Sources (dBA): Rail Joints	Rough Rails	Rough Wheels	Power Pickup	Propulsion	Auxiliary (Mechanical)	Auxiliary (Aeroacoustic)
86	Pa + Pb	85	73	73	56	77	68	-
94	Pc + Pd + Pb	92	87	87	70	77	-	-
81	Pe + Pd + Pb	79	73	73	65	-	-	-
65	Pf	-	-	-	-	-	-	65
95	Total	93	87	87	71	80	68	65

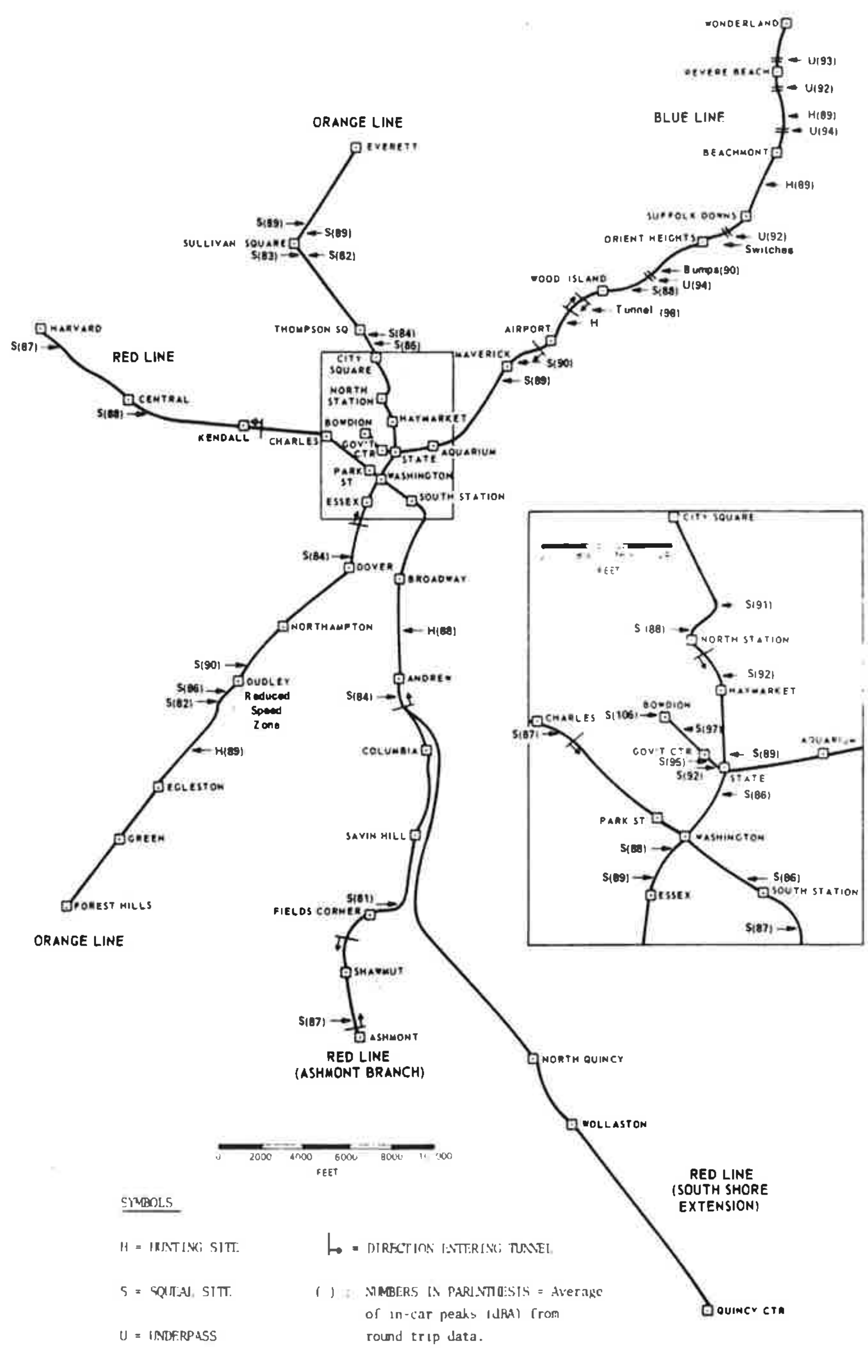


Figure 2.3 Site-Specific In-Car Noise Problems

or meter was placed about ten feet back from the platform edge at a typical waiting location. In the absence of any train, waiting patrons hear ambient noise due to station machinery and, if the station is above ground, from traffic and aircraft. As a train arrives the awaiting patrons hear mostly low frequency noise. Usually the noise level reaches a peak in about six to eight seconds and drops rapidly during the next several seconds to a rough noise plateau as the train stops. Frequently, the mechanical tread-braking produces a short screech prior to the stop. In the worst cases, the following effects then occur in rapid succession: (1) door slam; (2) brake air release hiss; (3) auxiliary equipment such as ventilation and motor-generators produce a steady noise. As the train departs another sequence of door slam and brake hiss noises occur followed by the low frequency rumble of the departing train. Figure 2.4 is an example of the above sequence of noise events.

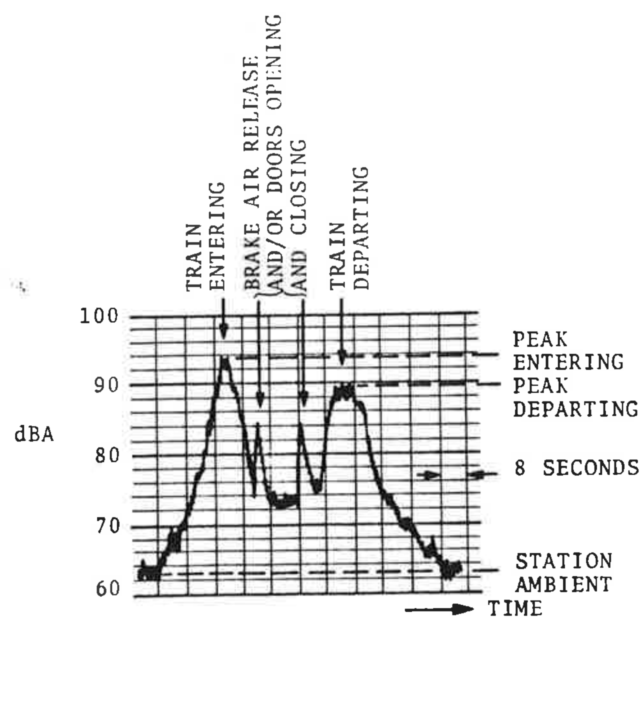


Figure 2.4 Sample Time History of In-Station Platform Noise Levels (dBA)

While it is recognized that rapidity of brake air releases and door operation can startle or annoy patrons in the station, a quantification of such annoyance is not within the scope of the present effort.

The average of the arriving and departing peaks in the A-weighted sound levels was chosen as a simple measure of the severity of noise in stations. This data is shown on the picto-rail summaries, Figure 2.7 at the end of this section.

For unmeasured stations, noise levels were estimated from measurements on similarly constructed stations on the same line. Table 2-3 lists noise levels, measured or estimated, for all stations in the system.

2.2.3 Community Noise

Eleven sites were selected for community noise measurements. The sites were chosen from informal complaint data obtained from discussions with MBTA, and from study of the proximity of the right-of-way to neighboring residential, commercial, and industrial communities.

In the absence of any rapid transit trains an observer at a wayside site is exposed to an ambient noise level generally due to motor vehicles, aircraft, children playing, wind, and industrial noise. As the train approaches, passes, and recedes from the observation point, the A-weighted sound pressure level rises to a maximum, then falls back to ambient. Figure 2.5 shows a sample time history of A-weighted sound pressure level at a measurement site during the pass-by of two 2-car trains. Depending on the specifics of the situation, the noise may comprise roar, multiple impacts (from joints or wheel flats), or squeal.

At each site, the sound pressure level of several trains was measured in an open area at the same distance from the track as typical wayside structures. The data shown are averages of the measured maximum levels.

TABLE 2-3 (1 of 2) SUMMARY OF STATION PLATFORM NOISE FOR MBTA BLUE, ORANGE AND RED LINES

SUMMARY OF BLUE LINE STATION PLATFORM NOISE

TRACK TYPE	97-93 DBA			92-88 DBA				87-83 DBA			
	LENGTH	STATION*	TYPE	LENGTH	STATION*	TYPE	SCENARIO*	LENGTH	STATION*	TYPE	SCENARIO*
GRADE				1860	6,7,9,10, 11,12	A	S4	310	8	A	[illegible]
TUNNEL				220	3	A	S2	200	[illegible]	[illegible]	[illegible]
TUNNEL				960	[illegible]	B	S3				
TUNNEL				480	1	[illegible]	S3				

SUMMARY OF ORANGE LINE STATION PLATFORM NOISE

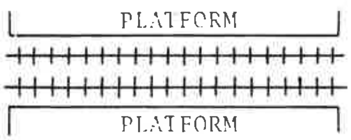
TRACK TYPE	92-88 DBA	87-83 DBA				82-78 DBA			
		LENGTH	STATION*	TYPE	SCENARIO*	LENGTH	STATION*	TYPE	SCENARIO*
ELEVATED		350	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ELEVATED		290	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ELEVATED		410	4	[illegible]	[illegible]	[illegible]	[illegible] 13	[illegible]	[illegible]
TUNNEL		2920	6,7,8,9	A	S5				

SUMMARY OF RED LINE STATION PLATFORM NOISE

TRACK TYPE	97-93 DBA				92-88 DBA				87-83 DBA			
	LENGTH	STATION*	TYPE	SCENARIO*	LENGTH	STATION*	TYPE	SCENARIO*	LENGTH	STATION*	TYPE	SCENARIO*
GRADE									2110	10,11,15, 16,17	B	S8
GRADE									310	12	A	S7
TUNNEL	590	2,3	A	S1	1380	6,7,9, 13,14	A	S2				
TUNNEL					360	8	B	S3				
TUNNEL					610	1	I	S3				
TUNNEL					360	5	F	S3				
ELEVATED									310	4	A	S9

TABLE 2-3 (2 of 2) TRACK CONFIGURATIONS

A



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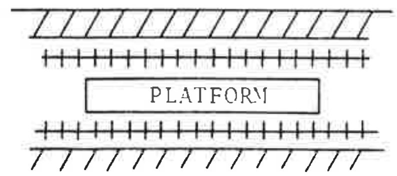

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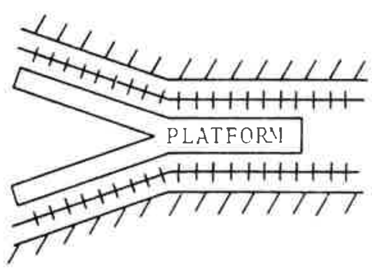

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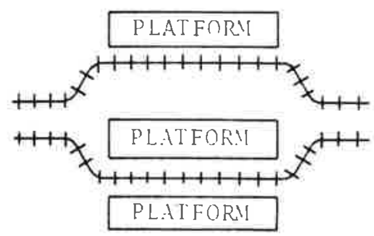

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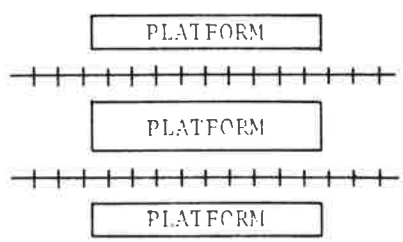

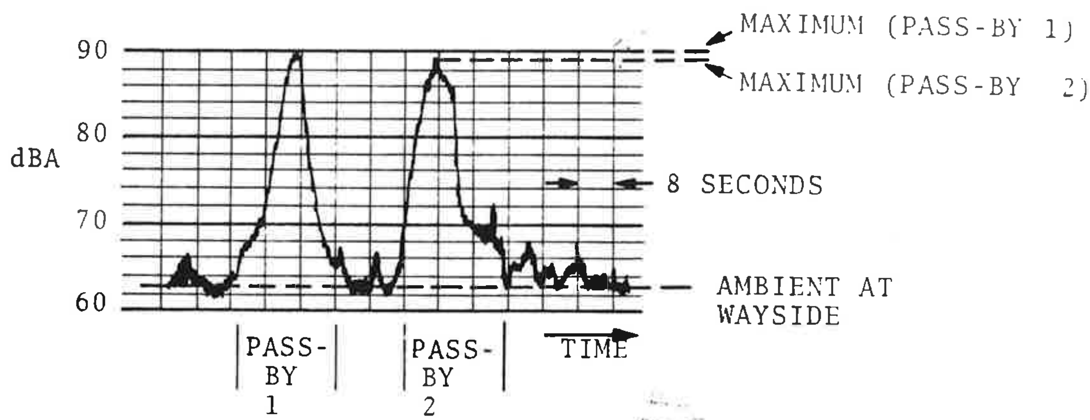

Figure 2.5 Sample Time History of Wayside Noise Levels (dBA) - Pass-By of Two Car Trains

The relationship of these data to the wayside communities can be seen in the overall pictorial summaries, Figure 2.7, at the end of this section. This figure shows schematically the measured levels and the approximate distance to the nearest wayside structure (residential or commercial/industrial). Isolated structures deviating from the general pattern of a community are not shown.

The sound pressure level at the nearest wayside structures due to the pass-by of a typical train varies with location along a line (due to changes in roadbed and operating speed). The level also varies with distance from the right-of-way due to geometrical spreading of the acoustic energy from the train. These effects can be incorporated approximately in estimating noise levels at sites.

Each between-station length of the right-of-way adjacent to residential communities has been divided into one or more segments according to the typical distance to the nearest residences. These segments are labelled on Figure 2.7. Estimated wayside levels maximum pass-by A-weighted sound pressure levels) were determined for each segment by correcting one or more of the wayside site measurements for geometrical spreading. Spreading was calculated by modeling the train as a 300 foot long incoherent line source.

Table 2-4 lists the pass-by noise levels thus obtained for segments of the right-of-way adjacent to residences. The secenario numbers in the table refer to scenarios defined in Appendix B.

TABLE 2.4 LINE SUMMARIES FOR RESIDENTIAL PASS-BY NOISE

Peak Pass-by Level		95 dBA			90 dBA			85 dBA			80 dBA		
MBTA LINE	TRACK TYPE	LENGTH (FT)	TRACK SEGMENTS	SCENARIO #	LENGTH (FT)	TRACK SEGMENTS	SCENARIO *	LENGTH (FT)	TRACK SEGMENTS	SCENARIO *	LENGTH (FT)	TRACK SEGMENTS	SCENARIO *
BLUE LINE	AT GRADE				2600	9b,10b	C1	[illegible]	6c,7b,8c, 10c,10d	[illegible]	3650	[illegible]	C3
ORANGE LINE	ELEVATED	1860	10b	C4	18980	[illegible],5,9b, 10c,11b, 13,14	C5				1000	12a	C6
RED LINE	AT GRADE (JOINTED)				5610	9b,10b	C1	2640	11b	C2	1380	[illegible]	C3
	AT GRADE (WELDED)							13300	14b,c, 15a,16	C7			
	ELEVATED (JOINTED)				510	15	C5						
	ELEVATED (WELDED)							850	13	C8			

Locations of track segments are given in figure 2.[illegible]

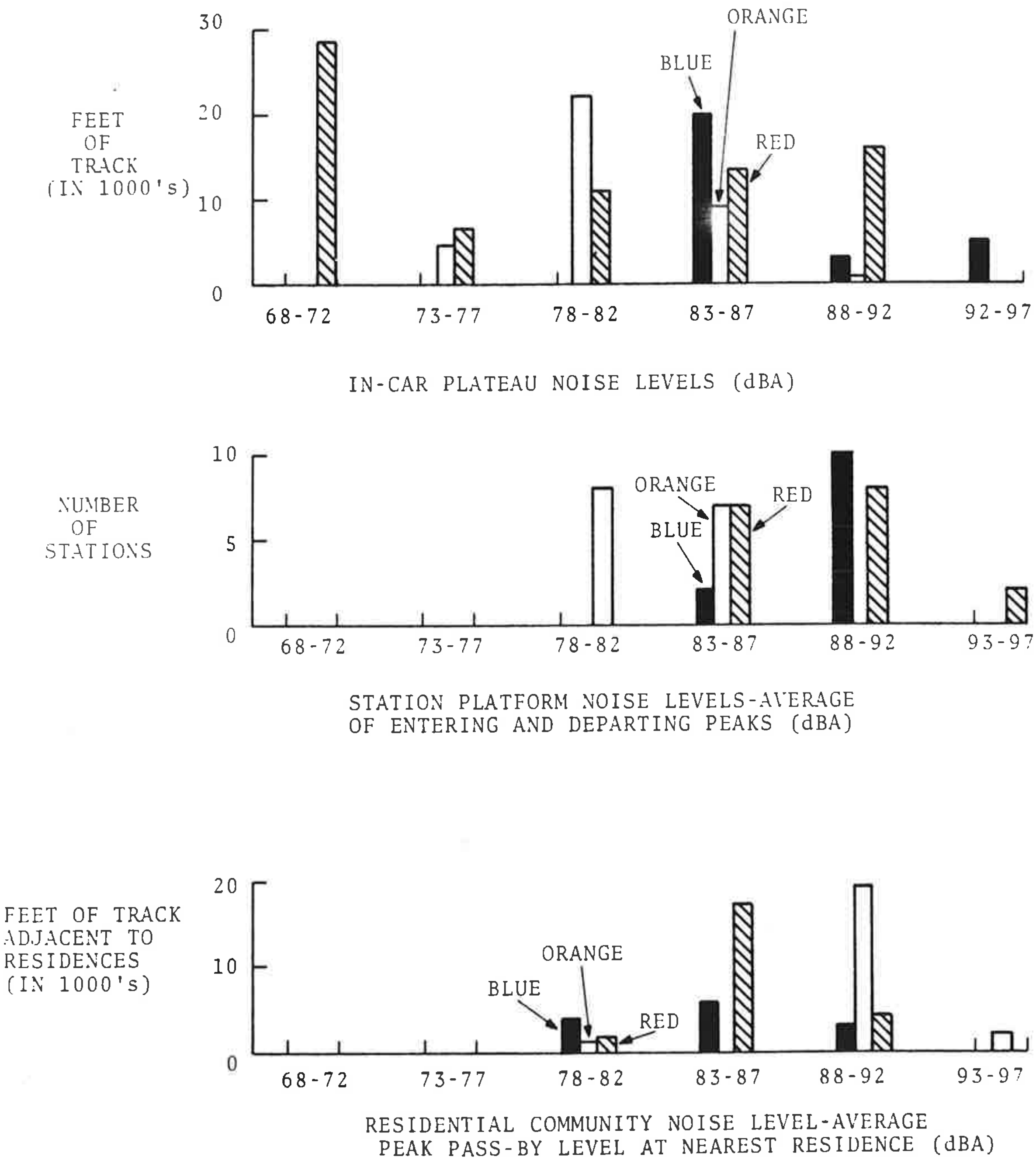

Figure 2.6 Summary of MBTA Noise Status

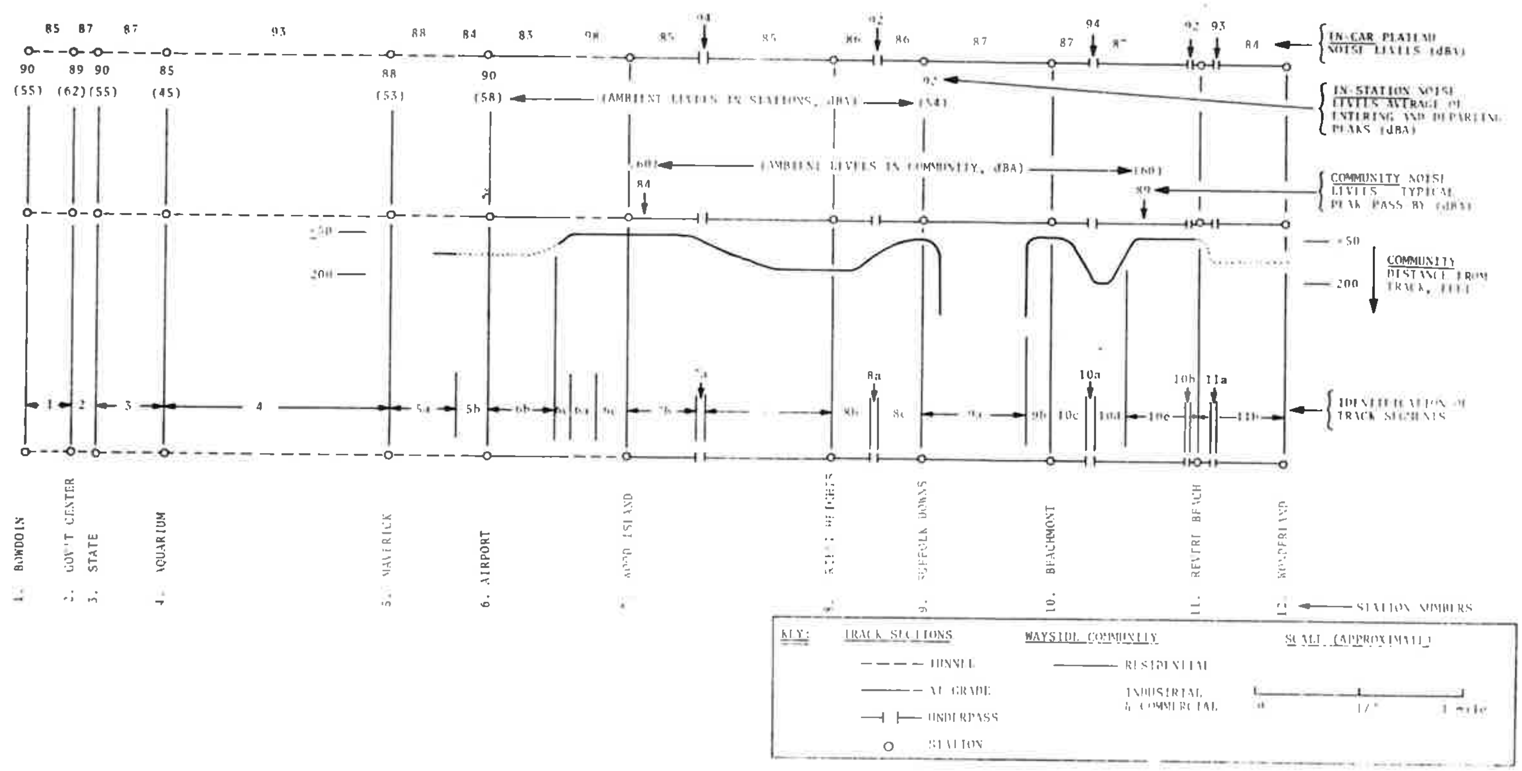

Figure 2.7 (1 of 3) MBTA Blue Line Noise Measurement Summary

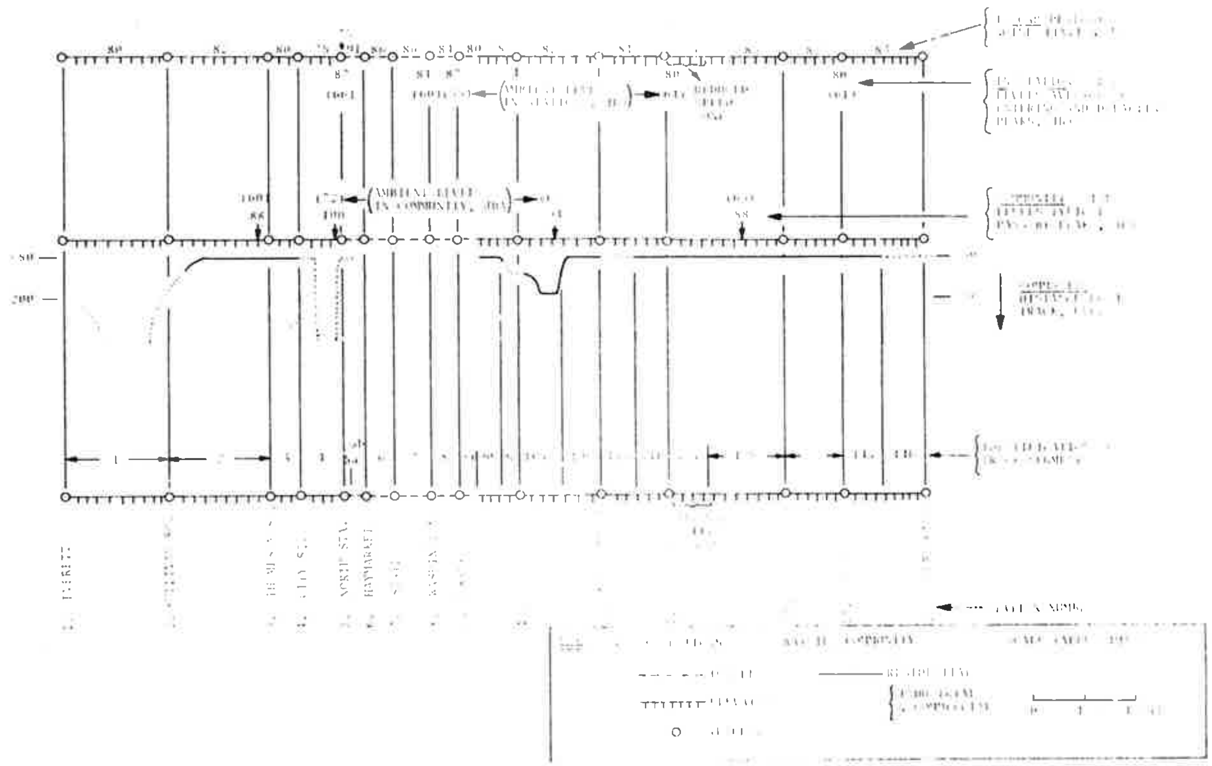

Figure 2.7 (2 of 3) MBTA Orange Line Noise Measurement Summary

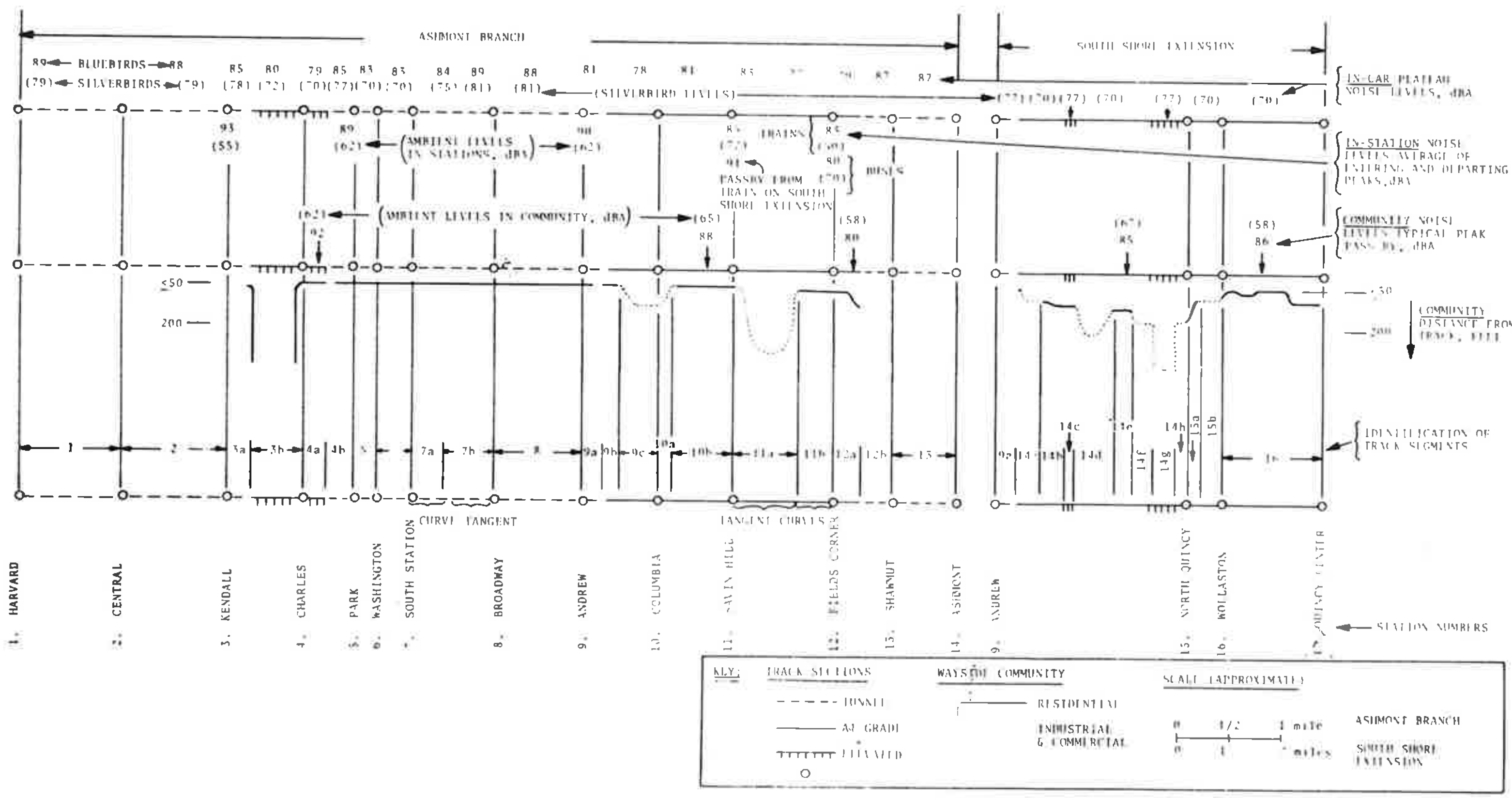

Figure 2.7 (3 of 3) MBTA Red Line Noise Measurement Summary

3. ASSESSMENT OF ABATEMENT OPTIONS AND COST/ABATEMENT ANALYSIS

3.1 METHODOLOGY

3.1.1 Introduction

A simplified methodology has been developed for a first order analysis of noise levels, sources, paths, abatement techniques, and abatement costs. This leads to a first order assessment of abatement options. The assessment methodology could be applied generally to any rapid transit property. However, in this report a pilot application is made to MBTA.

Many diverse factors affect the noise climate and control in urban rapid rail systems. These factors include the design and age of the track, the design and age of the car, type of community, type of station, operation speeds, wheel conditions, etc.

The approach to the derivation of abatement/cost requirements is as follows. From measurements, under various conditions, estimates are made of the most important sources and paths and of the contribution to the total noise level associated with the specific source-path. Then, attacking the worst offenders first, the proper abatement technique is selected. This strategy keeps the work within limits by breaking down the total line into segments of similar noise level, track type, etc. and treats entire sections at a time.

The methodology is presented briefly here, and in more detail in Appendix B. The clerical tasks required to execute the methodology may be programmed for a digital computer in a direct manner. The summary of the methodology, given immediately below, serves as a synopsis for the remainder of Section 3.1.

COST/ABATEMENT METHODOLOGY SUMMARY

1. Measure or estimate the overall level and the contribution of each rapid transit source to the noise at the receivers.
2. Identify each path and estimate the relative contribution to total level transmitted by each path.
3. For estimating purposes, group together similar segments of the system right-of-way (similar in source and path contributions to typical receivers).
4. Calculate the new overall levels for each group based on attenuating one or more sources or paths by various combinations of noise control techniques.
5. Calculate cost estimates for each combination of techniques applied to the groups of segments.
6. Calculate total system cost to achieve each of several reduced levels of noise at the receiver locations, using the lowest-cost combinations of techniques.

3.1.2 Noise Sources, Paths, and Receivers in Rapid Transit Systems

As is usual in noise control, it is simplest to deal with rapid transit noise control problems when the acoustics is divided into noise source, propagation path, and receiver. Important sources, paths, and receivers for rapid transit systems are listed in Table 3-1. For each of the sources and paths listed, there are one or more techniques which, if applied to the single source - path combination would result in a reduction in the noise at the receiver. With multiple sources and paths operating, the reduction of noise from a single source (or path) will have significant effect (on the sound pressure level) only if that source (or path) strongly dominates the others. For example, this is generally the case for wheel squeal. This noise can dominate other sources by as much as 20 dBA. Squeal, however, is an exception in this regard. It is more typical of rapid transit noise for several

TABLE 3-1 RAPID TRANSIT NOISE SOURCES, PATHS AND RECEIVERS -

SOURCES	PATHS & SECONDARY RADIATORS	RECEIVERS
Curved Track (Flange Rubbing & Wheel Squeal)	Airborne Paths	Patrons & Employees
Rail Discontinuities:	Direct	In Vehicle
Joints	Reflected	In Station
Switches	Reverberation in Tunnels	Wayside Community
Crossovers	Reverberation in Stations	
Defects	Reverberation in Vehicles	
Rail Roughness:	Structure borne Paths:	
Random	Suspension Systems (Vehicle / Aux. Equip. / Prop. Equip.)	
Corrugation		
Wheel Roughness:		
Random	Vehicle Structure Transmission Loss	
Flats	Guideway Vibration Transmission	
Power Collector	Ground borne Vibration Path	
Propulsion Equipment		
Auxiliary Equipment		
Generators		
Compressors	Secondary Radiators:	
Air Conditioners	Vehicle Walls	
Door Operation	Guideway Support Structure	
Brake System	Adjacent Building Structures	
Air Venting	Station Structures	
Brake Squeal		
Primary Radiation from each Source		

sources or paths to contribute more-or-less equally. So in general, it is necessary to control the noise from each of several sources transmitted along several paths to several receivers. The total sound pressure level at the receiver must then be calculated from the sum of the source-path contributions.

Strictly speaking the sound power, frequency content, and directivity of each source is a continuously varying function of train speed and location along the track. Propagation paths, too, vary with location along the track. The system is therefore divided into a number of segments, the fundamental assumption being that sources, paths, and receivers can be approximated by some average values over the segment. For each rapid transit line this means, essentially, that the overall noise control problem is posed as a collection of independently posed segment-problems whose solutions cannot be determined independently because any noise control methods applied to the railcars will affect all track sections.

3.1.3 Noise Control Techniques

In general, abatement techniques which directly effect a noise source will result in equal attenuation of the noise levels due to that source at each receiver. However, noise path control techniques do not necessarily result in equal abatement for each receiver. Reflective wayside barriers, for example, can reduce community noise but may increase noise levels in the car.

Table 3-2 presents a summary of the source or path attenuation which can be expected in applying known noise control techniques to rapid transit systems. Each attenuation applies only to the sources and paths designated, when existing in isolation, so in the general case they would not correspond to the overall reduction at a receiver when several sources or paths contribute. This point must be clearly understood if misuse of Table 3-2 is to be avoided.

TABLE 3

ABATEMENT TECHNIQUE	NOISE SOURCE OR PATH AFFECTED	REDUCTION POTEN
DAMPED WHEELS	Wheel Squeal Roar (due to wheel & rail roughness) Impact (due to joints & wheel flats)	Eliminates So 1 dBA 1 dBA
RESILIENT WHEELS	Wheel Squeal Roar (due to wheel & rail roughness) Impact (due to joints & wheel flats)	Eliminates Sourc 2 dBA 2 dBA
INTERIOR CAR ABSORPTION	Reverberant level in car	3 dBA
ACOUSTIC SEALING OF CAR (improved door seals, ventilation duct lining)	Lower car body transmission loss Upper car body transmission loss	5 dBA 10 dBA
WHEEL TRUING	Impact (due to wheel flats) Roar (due to random wheel roughness)	Eliminates Sourc 5-7 dBA
DOOR MECHANISM- repair and maintenance	Mechanical noise from door operation	10 dBA
AIR BRAKE VENT MUFFLERS	Venting of air from brake air compressors	15 dBA
NEW CAR:		
a. Interior Car Absorption	Reverberant level in car	5 dBA
b. Acoustical Sealing of Car Openings	Overall car body transmission loss	10 dBA
c. Trued Wheels	Wheel flats & random roughness	eliminates flats
d. Improved Door Mechanism Design	Mechanical noise from door operation	10 dBA
e. Air Brake Vent Mufflers	Air venting from brakes	15 dBA
f. Double-pane Windows	Overall car body transmission loss	2 dBA
g. Car Wall Panel Damping	Structure borne noise	5 dBA
h. Improved Motor/Gear Design	Propulsion system noise	10 dBA
i. Vibration Isolation of Auxiliary Eq.	Structure borne noise	10 dBA
j. Improved Vehicle Suspension	Structure borne noise	10 dBA
k. Acoustical Isolation	Auxiliary & propulsion Airborne Noise	5 dBA
REDUCE VEHICLE SPEED	Wheel/Rail Noise Sources (Impact and Roar) Propulsion Noise	9dBA/halving of average of wheel and propulsion n

*Note: This Table is designed for use in the method described in this report. Use in other methods could lead to erroneous conclusions

TABLE 3-2 (1 of 2) RAPID TRANSIT NOISE ABATEMENT TECHNIQUES - CAR TREATMENT

CE OR PATH AFFECTED	REDUCTION POTENTIAL *	INITIAL COST	MAINTENANCE
Wheel Squeal heel & rail roughness) joints & wheel flats)	Eliminates Source 1 dBA 1 dBA	$800/car ($100/wheel for adding damping to existing wheel)	Same as stan wheels.
Wheel Squeal heel & rail roughness) joints & wheel flats)	Eliminates Source 2 dBA 2 dBA	$4000/car ($500/wheel for new wheels)	Same as stan wheels
level in car	3 dBA	$1000/car ($2/ft.^{2} x 500 ft.^{2} - floor or ceiling area)	Assumed negl
transmission loss transmission loss	5 dBA 10 dBA	$100/car (estimate)	Assumed negl
to wheel flats) andom wheel roughness)	Eliminates Source 5-7 dBA	$250,000 (purchase & installation of wheel truing machine)	$100/car onc ($25/wheel s 4 wheel sets
se from	10 dBA	$600/car $100/door x 6 doors/car -estimate)	$30/car/year (estimate)
from brake s	15 dBA	$50/car	None
vel in car dy transmission loss random roughness se from door operation om brakes dy transmission loss e noise tem noise e noise e noise opulsion Airborne	5 dBA 10 dBA eliminates flats, 5-7 dBA (wheel roughness) 10 dBA 15 dBA 2 dBA 5 dBA 10 dBA 10 dBA 10 dBA 5 dBA	$350,000/car	Maintenance items c and same as abov
se Sources ar) se	9dBA/halving of speed average of wheel trail and propulsion noise)	None	None

described in
l to erroneous

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	MAINTENANCE COST	REMARKS
1)	Same as standard wheels.	a) May be problem with long term bonding b) Treatment could prevent visual inspection of wheels c) Investigation needed into thermal effects during tread braking d) Several designs available.
	Same as standard wheels	a) Can be damaged by overheating b) Less wear of wheel tread claimed c) May contribute to rail corrugation (needs investigation) d) Several designs available
oor	Assumed negligible	a) Vandalism may be a problem b) Effectiveness of treatment may deteriorate if material becomes clogged with dirt c) Limited tests n eded to choose material and method of application
	Assumed negligible	a) Testing needed to determine best method and material for "sealing" car.
	$100/car once/year ($25/wheel set x 4 wheel sets/car)	a) Can reduce wear on rails b) Increases life of wheels
	$30/car/year (estimate)	a) Requires investigation into causes of noisy door operation
	None	
	Maintenance for items c and d same as above	a) Should be able to achieve an upper limit of 75 dBA in car. b) Effect on wayside noise levels is small except for the result of maintaining true wheels.
	None	a) May only be practical on short stretches of track

ABATEMENT TECHNIQUE	NOISE SOURCE OR PATH AFFECTED	RE
WELDED RAIL	Impact at Rail Joints	Elimina
IMPROVED JOINTS (bolted-epoxy joints)	Impact at Rail Joints	
RAIL GRINDING	Roar (Due to Rail Roughness) Soilborne Vibrations	2 (New 8 (Corr
RAIL LUBRICATION	Wheel Squeal	
ADJUSTMENT OF TRACK GEOMETRY	Ride Comfort Flange Impact	5 dB
RESILIENT RAIL FASTENERS	Soilborne Vibrations Secondary Radiation from Elevated Structures	
RESILIENTLY MOUNTED CONCRETE SLAB	Soilborne Vibrations	
BARRIERS: NON-ABSORPTIVE ABSORPTIVE	Direct Radiation to Community	
DAMPING OF STEEL ELEVATED STRUCTURES	Secondary Radiation from Elevated Structures	
ABSORPTIVE TREATMENT IN TUNNELS a. SIDE WALLS b. CONCRETE INVERT c. BOTH (a & b)	Reverberant Level Outside Car	
STATION TREATMENT a. CEILING b. WALLS ABSORPTION: c. UNDER-PLATFORM d. CONCRETE INVERT e. ABSORPTIVE BARRIERS BETWEEN TRACKS	Reverberant Level in Station Reverberant Level in Station Direct Radiation to Opposite Platfrom	(assume with tr

TABLE 3-2 (2 of 2) RAPID TRANSIT NOISE ABATEMENT TECHNIQUES - LINE TREATMENT

REDUCTION POTENTIAL	INITIAL COST (PER DOUBLE TRACK FOOT)	MAINTENANCE COST (PER DOUBLE TRACK FOOT)
Eliminates Source	\$25/ft. $\left(\frac{\$250}{\text{join}} \times \frac{1\ \text{joint}}{39\ \text{ft}} \times \frac{4\ \text{rails}}{\text{double track}}\right)$	None
5 dBA	\$5/ft. (\$50/joint)	None
2 (New Rail) 8 (Corrugated Rail) dBA	————	\$2/ft./year (\$.25/ft./track x 2 track. x 4 times/year)
15 dBA	\$4000/curve (estimate)	Assumed Negligible
———— 5 dBa (Estimate)	————	\$2/ft./year (once/year)
5 dBA 10 dBA	\$8/ft. (\$2/fastener,2ft spacing; \$4/ft. labor)	None
15-20 dBA	\$300/ft. (estimate)	None
10-14 dBA 12-16 dBA	(4 5 ft barriers/double track) \$80/ft. (\$4/ft^2) \$100/ft. (\$5/ft.^{2})	Negligible Negligible
8-12 dBA	\$100/ft (estimated)	None
5 dBA 5-9 dBA 10-12 dBA	(Divided Tunnel: 4 ft. high on 4 walls) Undivided " 8 ft. high on 2 walls \$32/ft. \$18/ft. (\$2/ft.^{2}) \$50/ft.	Negligible
(assumes station configuration with tracks between platforms) 7 dBA 5 dBA 3 dBA 5-7 dBA 5 dBA 12-16 dBA	\$160/ft. (40' wide) \$4/ft.^{2} \$64/ft. (8'high, 2 walls) \$16/ft. (4'high, 2 platforms) \$18/ft. (4'1/2 wide, 2 tracks $\frac{\$2}{ft^2}$ \$25/ft.(5'high \$5/ft^2)	Negligible

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	MAINTENANCE COST (PER DOUBLE TRACK FOOT)	REMARKS
	None	a. Field welds must be expertly done in order to avoid dips at joints. b. Welded rail may be incompatible with existing elevated structures. c. Not used on small radius curves
	None	a. Can be used wherever welded rail is incompatible with system
	$2/ft./year ($.25/ft./track x 2 tracks x 4 times/year)	a. Does not decrease life of rail due to excessive wear
	Assumed Negligible	a. Numerous types of lubrication schemes are available. Both wet and dry lubricants have been used. b. Problems with loss of braking traction have occured c. Some properties supply rail lubrication over entire system.
	$2/ft./year (once/year)	a. Performed mostly on curves. b. Should be combined with standard roadbed maintenance such as upgrading ballast and replacing ties.
	None	a. Use primarily with concrete ties or direct fixation to concrete invert.
	None	a. Used at locations requiring special treatment for soilborne vibrations. b. Design of "floating" slabs is still being perfected
	Negligible Negligible	a. Non-absorptive barriers increase reverberation outside the car by 3-5 dBA b. Barriers should be placed as close to track as possible c. Barriers on elevated structures do not reduce the secondary radiation from the structure.
	None	a. Added weight may endanger structure
4 walls) 2 walls	Negligible	a. Absorptive treatment should be water resistant and non-combustible
2 $\frac{\$2}{ft^2}$	Negligible	a. Reduction potential of station treatments depends considerably upon station configuration. b. Absorptive treatment on walls is more effective when platform lies between tracks. c. Vandalism and dirt in stations may be a problem

Included in Table 3-2 are the approximate (or estimated) costs of implementing each noise control technique. This is divided into the initial cost and the maintenance costs per year. The total dollar costs for a given technique for the MBTA example were calculated simply as the sum of the initial cost plus maintenance costs for ten years. The accuracy of the estimated values probably does not warrent more elaborate costing methods at this time. Only materials and labor costs are included in the estimate. Engineering services and overhead are not included.

3.1.4 Cost and Noise Reduction Estimates

Table 3.2 is also used in conjunction with scenarios to calculate the noise reduction and cost of combinations of abatement techniques.

The method is as follows:

1. Compute the noise reduction potential of individual and combinations of abatement techniques applied to a given scenario.
2. Compute the cost for the technique combinations which result in the desired degree of abatement.
3. Choose the technique which results in the minimum cost. Where simultaneous abatement of several scenarios is required, a trade-off must be made between car and track oriented abatement techniques.

3.2 MBTA COST/ABATEMENT OPTIONS

The present overall MBTA noise climate is summarized in different ways in Figure 2.6 and 2.7; Tables 2-1, 2-3, and 2-4 provide further detail backup. A variety of strategies could be followed to develop an efficient way of allocating resources for noise reduction. For example improvements could be made only at complaint locations; or uniform improvements could be made on all rights of way not scheduled for abandonment within ten years.

For the purpose of obtaining gross estimates of the cost, two strategies were considered in this report. Both assume that, initially, the sources classified as singularities have been treated. The "base" cost for abatement of these singularities includes track geometry maintenance to reduce flange impact, damped or resilient wheels to reduce squeal, air brake vent mufflers and door mechanism maintenance. These costs are treated independently in the initial stage of the general cost analysis methodology and represent an initial expense to be added to the costs of further abatement. Table 3-3 shows a detailed breakdown by line, source type and receiver.

The first abatement strategy starts with the question: Suppose only one receiver type were considered important, how much would it cost to reduce the present levels at that type of receiver to 90, 85, 80 and 75 dBA? As a general rule noise control techniques which succeed in reducing the levels in, say, the stations, would result in somewhat reduced levels elsewhere, that is, in the car and in the community. In this strategy this effect is a fortunate bonus. The minimum costs for abatement, (excluding the base costs) considering one type of receiver at a time, were computed for the Blue, Orange, and Red Lines, respectively and are shown in Table 3-4. Different levels of abatement and the necessary techniques to minimize costs are shown. The total costs were then computed by adding the "base" costs discussed above. A "normalized" cost is shown in the Table as a simple measure of cost effectiveness for combinations of abatement techniques.

The second abatement strategy asks the question: Suppose it were desired to equalize the maximum A-weighted sound levels at all three receivers; how much would it cost to reduce the present levels to no more than 90, 85, 80, and 75 dBA at all three classes of receivers? Table 3-5 shows the cost/abatement options available under the second abatement strategy. In general, adding the costs for rider, station, and community target noise levels from Table 3-4 would be overly conservative for two reasons. First the cost for a given technique applied to the car or to a specific

TABLE 3-3 BASE COSTS FOR ACHIEVEMENT OF 90 dBA NOISE LEVEL ON MBTA BY ELIMINATION OF NOISE SINGULARITIES

TABLE 3.3 BASE COSTS FOR ACHIEVEMENT OF 90dBA NOISE LEVEL ON MBTA BY ELIMINATION OF NOISE SINGULARITIES

TREATMENT \ LINE	TREATMENT COSTS ($K) OVER 10 YEARS		
	BLUE	ORANGE	RED
1. Damped Wheels	120	160	269
2. Track Geometry Adjustment (over 10% of line)	111	124	289
3. Door Maintenance for Mechanical Operation	68	90	106 (initial cost not included for Silverbirds)
4. Air Brake Vent Mufflers	4	5	8

RECEIVER \ LINE	TOTAL BASE COST ($K) TO EACH RECEIVER		
	BLUE	ORANGE	RED
RIDER (1+2+3+4)	303	379	672
STATION (1+3+4)	192	255	383
COMMUNITY (1+2)	231	284	558
ALL RECEIVERS (1+2+3+4)	303	379	672

TABLE 3-4 (1 of
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RECEIVER / DESIRED LEVEL (dBA)	RIDER				
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	NORMALIZED COST (b) ($/dBA)	SCENARIO # (b)
90	R1	Seal Car	75	3.0	-
85	R1, R2	Seal Car, Interior Car Absorption	150	2.3	S2, S3, S4 S3, S2
80	R1 R1, R2, R3, R5	Weld Rail Seal Car, Interior Car Absorption	274	1.3	S2, S3, S4 S7, S7 S2, S3 S2, S4, S6, S7 S3 S2, S3
75	R1, R2, R5 R1 R1 R3 R1, R2 R3, R5	Weld Rail Grind Rail True Wheels Improve Joints Seal Car, Interior Car Absorption	970	2.8	S2, S3 S4, S6 S7 S2, S3, S4 S2, S4, S6 S3, S4 S2, S3 S3

FOOTNOTES: (a) The base costs, identified in Table 3.3 for elimination of noise singularities are not included in this table.

(b) Refer to Tables 2.1, 2,3 and 2.4 for identification of the track segments and stations covered by each scenario.

(c) The normalized cost is defined and explained in Section 3.2.

TABLE 3-4 (1 of 3) MINIMUM COST NOISE ABATEMENT ON THE MBTA BLUE LINE[(a)] - INDEPENDENT RECEIVERS

RIDER			STATION			
ABATEMENT TECHNIQUES	TOTAL COST ($K)	NORMALIZED COST (b) ($/dBA)	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	NORMALIZE COST (b) ($/dBA)
Seal Car	75	3.0	-	-	NONE	-
Seal Car, Interior Car Absorption	150	2.3	S2, S3, S4	Weld Rail Resilient Fastener	143	8.2
			S3, S2	Under Plat-form Treat-ment		
Weld Rail Seal Car, Interior Car Absorption	274	1.3	S2, S3, S4, S7, S7	Weld Rail Resilient Fastener	359	9.6
			S2, S3	Under Plat-form Treat-ment		
			S2, S4, S6, S7	Barrier		
			S3	Grind Rails		
			S2, S3	Wall Treatment		
Weld Rail Grind Rail True Wheels Improve Joints Seal Car, Interior Car Absorption	970	2.8	S2, S3, S4, S6, S7	Weld Rail Resilent Fastener	567	9.8
			S2, S3, S4	Under Platform Treatment		
			S2, S4, S6	Barrier		
			S3, S4	Grind Rails		
			S2, S3	Wall Treatment		
			S3	Ceiling Treatment		

dentified in Table 3.3 for elimination of noise singularities
in this table.
.1, 2,3 and 2.4 for identification of the track segments and
by each scenario.
st is defined and explained in Section 3.2.

IMUM COST NOISE ABATEMENT
BLUE LINE[a] - INDEPENDENT

STATION			COMMUNITY			
'EMENT INIQUES	TOTAL COST ($K)	NORMALIZED COST (b) ($/dBA)	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	NORMALIZED COST ($/dBA)
-	NONE	-	-	-	NONE	-
Rail lient ener r Plat- Treat-	143	8.2	C1	Weld Rail	65	5.0
Rail lient ener r Plat- Treat- ier d Rails tment	359	9.6	C1 C2	Barrier (Non-Absorp- tive) Weld Rail	351	6.4
Rail lent ener r form tment ier i Rails :ment .ng :ment	567	9.8	C1 C1, C2 C3	Improve Joints Barrier (Non-absorptive) Weld Rail	757	6.6

TABLE 3-4

RECEIVER / DESIRED LEVEL (dBA)	RIDER				
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST($K)	NORMAL-IZED COST(c) ($/dBA-ft)	SCENARIO # (b)
90	-	-	NONE	-	-
85	R2	Weld Rail Grind Rail	9	9.5	-
80	R2 R7 R2,R3, R7	Weld Rail Improve Joints Seal Cars	149	3.2	S5,S9 S10,S11, S10 S5,S9,S11
75	R2,R7 R3 R2,R3, R4,R7, R8	Weld Rail Improve Joints Seal Cars Interior Car Absorption	424	2.1	S5,S9 S10,S11, S12,S13, S14 S5,S9,S11 S12, S5,S9,S11

FOOTNOTES:
(a) The base costs, identified in Table 3.3, for elimination of noise singularities are not included in this table.
(b) Refer to Tables 2.1, 2.3 and 2.4 for identification of the track segments and stations covered by each scenario.
(c) The normalized cost is defined and explained in Section 3.2.

TABLE 3-4 (2 of 3) MINIMUM COST NOISE ABATEMENT ON THE MBTA ORANGE LINE - INDEPENDENT RECEIVERS

STATION				COMMUN	
SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	NORMAL-IZED COST(c) ($/dBA-ft)	SCENARIO # (b)	ABATEMENT TECHNIQUES
-	-	NONE	-	C4	Resilient R Fasteners
-	-	NONE	-	C4 C4,C5	Weld Rail Resilient R FASTENERS
S5,S9 S10,S11, S10 S5,S9,S11	Weld Rail Resilient Fastener Grind Rail Barrier	206	10.3	C4,C5 C4	Weld Rail Resilient R Fasteners Grind Rails True Wheels
S5,S9 S10,S11, S12,S13, S14 S5,S9,S11 S12, S5,S9,S11	Weld Rail Resilient Fastener Grind Rail Barrier UnderrPlat-form Treatment True Wheels	636	11.6	C4 C4,C5 C4,C5, C6	Barrier (Nc Absorptive) Weld Rail, Grind Rail, True Wheels Resilient F Fasteners

e singularities are

. segments and

AL-)(c) BA-ft)	COMMUNITY			
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST($K)	NORMAL-IZED COST (c) ($/dBA-ft)
	C4	Resilient Rail Fasteners	14	1.5
	C4 C4,C5	Weld Rail Resilient Rail FASTENERS	212	1.9
	C4,C5 C4	Weld Rail Resilient Rail Fasteners Grind Rails, True Wheels	725	3.3
	C4 C4,C5 C4,C5, C6	Barrier (Non-Absorptive) Weld Rail, Grind Rail, True Wheels Resilient Rail Fasteners	1386	4.2

TABLE 3-4 (3 of 3) I
ON THE MB'
RECEIVERS

RECEIVER / DESIRED LEVEL (dBA)	RIDER: SCENARIO # (b)	RIDER: ABATEMENT TECHNIQUES	RIDER: TOTAL COST ($K)	RIDER: NORMALIZED COST (c) ($dBA (a))	SCENARIO # (b)
90	-	-	NONE	-	S1
85	R2	Seal Cars	92	1.2	S1, S2, S3 S1
80	R2, R3, R5	Seal Cars, Interior Car Absorption	184	.8	S1, S2 S3, S9 S1, S2, S3 S1, S2, S9 S7 S8 S1, S2, S3
75	R2, (R9) R5 R3, R6 R9 R2, R3 R4, R5 R6, R8	Weld Rail Improve Joints True Wheels Seal Cars, Interior Car Absorption	801	1.9	S1, S2, S3, S9 S1, S2, S9 S3, S7, S8 S1, S2, S3 S7, S8, S9 S1, S2 S1

FOOTNOTES:
(a) The base costs, identified i
are not included in this tab
(b) Refer to Tables 2.1, 2.3, an
stations covered by each sce
(c) The normalized costs is defi

TABLE 3-4 (3 of 3) MINIMUM COST NO[illegible] ON THE MBTA RED LINE - I[illegible] RECEIVERS

RIDER				STATION		
SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	NORMALIZED COST (c) ($dBA (a))	SCENARIO # (b)	ABATEMENT TECHNIQUES	[illegible]
-	-	NONE	-	S1	Weld Rail Resilient Fasteners	
R2	Seal Cars	92	1.2	S1, S2, S3 S1	Weld Rail Resilient Fastener Barrier	1
R2, R3, R5	Seal Cars, Interior Car Absorption	184	.8	S1, S2 S3, S9 S1, S2, S3 S1, S2, S9 S7 S8 S1, S2, S3	Weld Rail Resilient Fastener Barrier Grind Rails Under Platform Treatment True Wheels	4
R2, (R9) R5 R3, R6 R9 R2, R3 R4, R5 R6, R8	Weld Rail Improve Joints True Wheels Seal Cars, Interior Car Absorption	801	1.9	S1, S2, S3, S9 S1, S2, S9 S3, S7, S8 S1, S2, S3 S7, S8, S9 S1, S2 S1	Weld Rail Resilient Fastener Barrier Grind Rails Under Platform Treatment Wall Treatment Ceiling Treatment True Wheels	9

FOOTNOTES:
(a) The base costs, identified in Table 3.3, for el[illegible] are not included in this table.
(b) Refer to Tables 2.1, 2.3, and 2.4 for identific[illegible] stations covered by each scenario.
(c) The normalized costs is defined and explained i[illegible]

COST NOISE ABATEMENT
INE - INDEPENDENT

TATION			COMMUNITY			
ES	TOTAL COST ($K)	NORMALIZED COST ($/dBA(a))	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	NORMALIZED COST ($/dBA(a))
	20	6.8	-	-	NONE	-
	127	6.6	C1 C5	Weld Rail Resilient Rail Fasteners	94	4.6
ls tform ls	443	8.9	C1 C2, C5 C5 C7, C8	Barriers (Non-Absorptive) Weld Rail Resilient Rail Fasteners True Wheels (Silver Birds Only)	448	2.7
ls tform tment reat- ls	997	12.5	C1 C3, C5 C8 C5 C1, C2 C5, C7 C8	Improve Joints Weld Rail Grind Rail, True Wheels (Silver Birds Only) Resilient Rail Fasteners Barriers (Non-Absorptive)	1851	5.7

, for elimination of noise singularities
dentification of the track segments and
plained in Section 3.2.

TABLE 3-5 ABATEMENT TECHNIQUES AND COSTS RESULTING IN EQUAL NOISE LEVELS AT EACH RECEIVER

LINE / DESIRED LEVEL (dB)	BLUE			ORANGE			RED		
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST ($K)
90	R1	Seal Car	[illegible]	C4	Resilient Fasteners	14	S1	Weld Rail, Resilient Fasteners	[illegible]
85	R1, S2 C1, S2, S3, S4 S2, S3, S4 S2, S3	Seal Car, Interior Car Absorption Weld Rail Resilient Fasteners Under Platform Treat.	358	R2, C4 R2 C4, C5	Weld Rail Grind Rail Resilient Fasteners	221	R2 C1, S1, S2, S3 C5, S1, S2, S3 S1	Seal Cars Weld Rail Resilient Fasteners Barriers (c)	[illegible]
80	R1, C2, S2, S3, S4, S6, S7 R1, R2, R3, R5 C2, S2, S4, S6, S7 S2, S3, S4, S6, S7 S2, S3 S3 S3, S3	Weld Rail Seal Cars, Interior Car Absorption Barriers (c) Resilient Fasteners Under Platform Treat. Grind Rail Wall Treat.	984	R2, C4, C5, S5, S9, S10, S11 R7 R2, R3, R7 C4, C5, S5, S9, S10, S11 C4, S10 S5, S9, S11	Weld Rail Improve Joints Seal Cars Resilient Fasteners Grind Rail Barriers (c) True Wheels	1080	R2, R3, R5 C4, C5, S1, S2, S3, S9 C5, S1, S2, S3 C1, S1, S2, S9 S7, S8 S1, S2, S3	Seal Cars Interior Car Absorption Weld Rail Resilient Fasteners Barriers Grind Rail Under Platform Treat. True Wheels	[illegible]
75	R1, R2, R5, C3, C2, S3, S4, S6, S7 R3, C1 R1, S3, S4 R1, R2, R3, R5 C1, C2, S2, S4, S6 S2, S3, S4, S6, S7 S2, S3, S4 S2, S3 S3	Weld Rail Improve Joints Grind Rail Seal Car, Interior Car Absorption Barriers Resilient Fasteners Under Platform Treat. Wall Treat. Ceiling Treat. True Wheels	2203	R2, R7, C4, C5, S5, S9, S10, S11, S12, S13, S14 R3 R2, R3, R4, R7, R8 C4, C5, S5, S9, S10-S14 C6 C4, S5, S9, S11, S12 S5, S9, S11	Weld Rail Imp. Joints Seal Cars Interior Car Absorption Grind Rail, Resilient Fasteners Resilient Barriers Under Platform Treat. True Wheels	2166	R2, R5, C3, C5, S1, S2, S3, S9 R3, R6 R2-R6, R8 C8, S3, S7, S8 C5, S1-S3, S9 C1, C2, C5, C7, C8, S1, S2, S9 S1-S3, S7-S9 S1, S2 S1	Weld Rail Improve Joints Seal Cars, Interior Car Absorption Grind Rails Resilient Fasteners Barriers Under Platform Treat. Wall Treat. Ceiling Treat. True Wheels	[illegible]

FOOTNOTES:
(a) The base costs defined in Table 3.3 have not been included here
(b) Refer to Tables 2.1 and 2.4 for the track segments covered by the rider and community scenarios, respectively. The stations covered by the Station scenarios are given in Table 2.3 for the Blue, Orange and Red Lines respectively.
(c) All station barriers are absorptive; all wayside barriers are non-absorptive.

track segment should be counted no more than once. This has been taken into account in Table 3.5 by subtracting any duplicate costs from the simple cost sum. Second, combining the techniques for the rider with those for the community will often reduce levels for both below the target level. This has not been taken into account; the effect probably does not exceed 5 dBA anywhere.

Normalized cost (C_n) is defined by the equation

$$C_n(X) = \frac{\text{total cost to abate to } X}{\sum_s L_s R_s}$$

where X is the level abated to, s is the segment (or station) number, R_s is the reduction in dBA calculated for segment (or station) s, and L_s is the length of the segment (or station) in feet. This measure of cost was developed in this study in anticipation of two future needs. The first need is for simple rule-of-thumb cost estimates for a wide variety of rapid transit noise control opportunities. Suppose the normalized cost were shown to be relatively insensitive to line length, amount of attenuation desired, age of line, and equipment, and so on. Then some average value, say $\overline{C}_n$, ought to be applicable to other systems directly:

$$C(X) = (\sum_s L_s R_s)\overline{C}_n,$$

where C(X) is the total cost to abate to some desired level. Figure 3.1 shows the normalized cost figures for the three MBTA lines over a 20 dBA range of abatement. About 75 percent of the data points lie between normalized costs of 2 to 10 $/FT/dBA. These values might then be used to determine upper and lower bound estimates on costs for abating other systems, at least for gross approximation. It should be noted that engineering costs are excluded as well as the base costs identified in Figure 1-1.

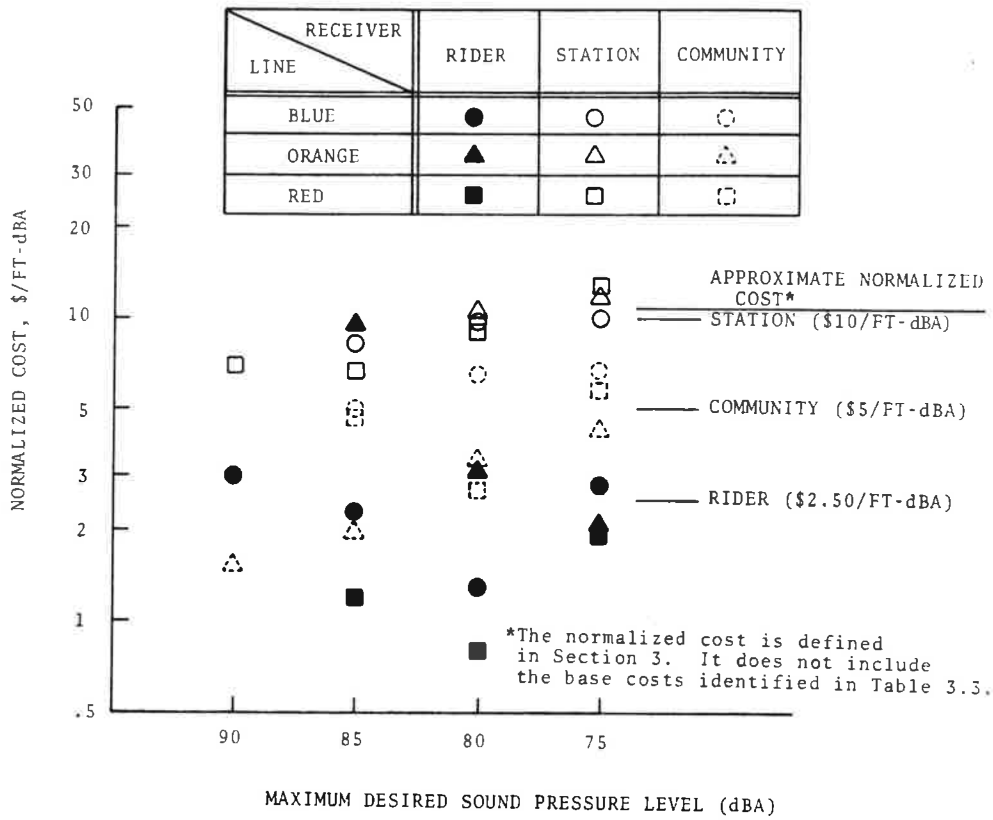

Figure 3.1 Dependence of Normalized Cost on Desired Abatement Level

A second use for normalized cost is in assessing the probable cost-effectiveness of new or improved techniques. New techniques which promise to have lower normalized costs than techniques presently available would tend to be most attractive for development

The two abatement strategies described above have incorporated some simplifying assumptions in order to arrive at a manageable methodology and rules for abatement. The first is that the noise level of the stations, wayside and car interiors is characterized in quantitative terms by an "average" of the maximum values which have greater duration and reproducibility than those of the very short transient effects classified as singularities. Second, the frequency of exposure of the several classes of receivers to the above average values is not factored into the cost estimate procedure. Thus the duration of a single noise event,

its rate of build-up and decrease and the repetition rate are not quantified in the methodology described. In effect it is assumed that a wayside resident is just as annoyed by one 90 dBA pass-by each ten minutes as by one each five minutes, and a rider is affected approximately the same by a ride which exposes him to 90 dBA between stations for two minutes as he is by a four minute exposure. Obviously a more refined model can attempt to include such additional parameters. However, much more data would be required for such a model and it is not obvious that conclusions about noise abatement techniques would result justifying the additional time and expense of such a detailed study.

4. HOW MUCH ABATEMENT?

This section provides a brief review of relevant material concerning Question (5), What noise limits (and the abatement goals) are desirable or might be required, which was posed in the first page of Section 1. The reader is referred to Figure 4.1, which summarizes the MBTA noise status and to Figure 4.2 which summarizes the cost of abatement versus the desired upper limit of noise. The question "how much abatement?" appears quite legitimate, in view of the fact that the slopes of the cost curves in Figure 4.2 are increasing rapidly as the upper noise limit is lowered. There is relatively little to be said regarding the desirability of eliminating the noise singularities (wheel squeal, noisy doors, air brake vents, etc.) present in the system. These noise singularities are generally considered particularly annoying and their elimination cost is relatively modest.

Regarding the horizontal scales of Figures 4.1 and 4.2, the following information is helpful for comparison and orientation purposes: (a) the sound level of one's own voice as measured at the ear is in the range of 72 to 82 dBA. Environments where the sound level is above this are generally considered "noisy". (b) The average interior noise levels in transportation vehicles are as follows:*

Passenger Cars	78dBA
Buses	82dBA
Passenger Trains	68 to 70dBA
Commercial Aircraft	82 to 83dBA

For comparison note that the in-car noise of the three MBTA rapid transit lines was found here in the range 70 to 95dBA, with a gross average of about 81dBA.

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*See Reference 15, Appendix C

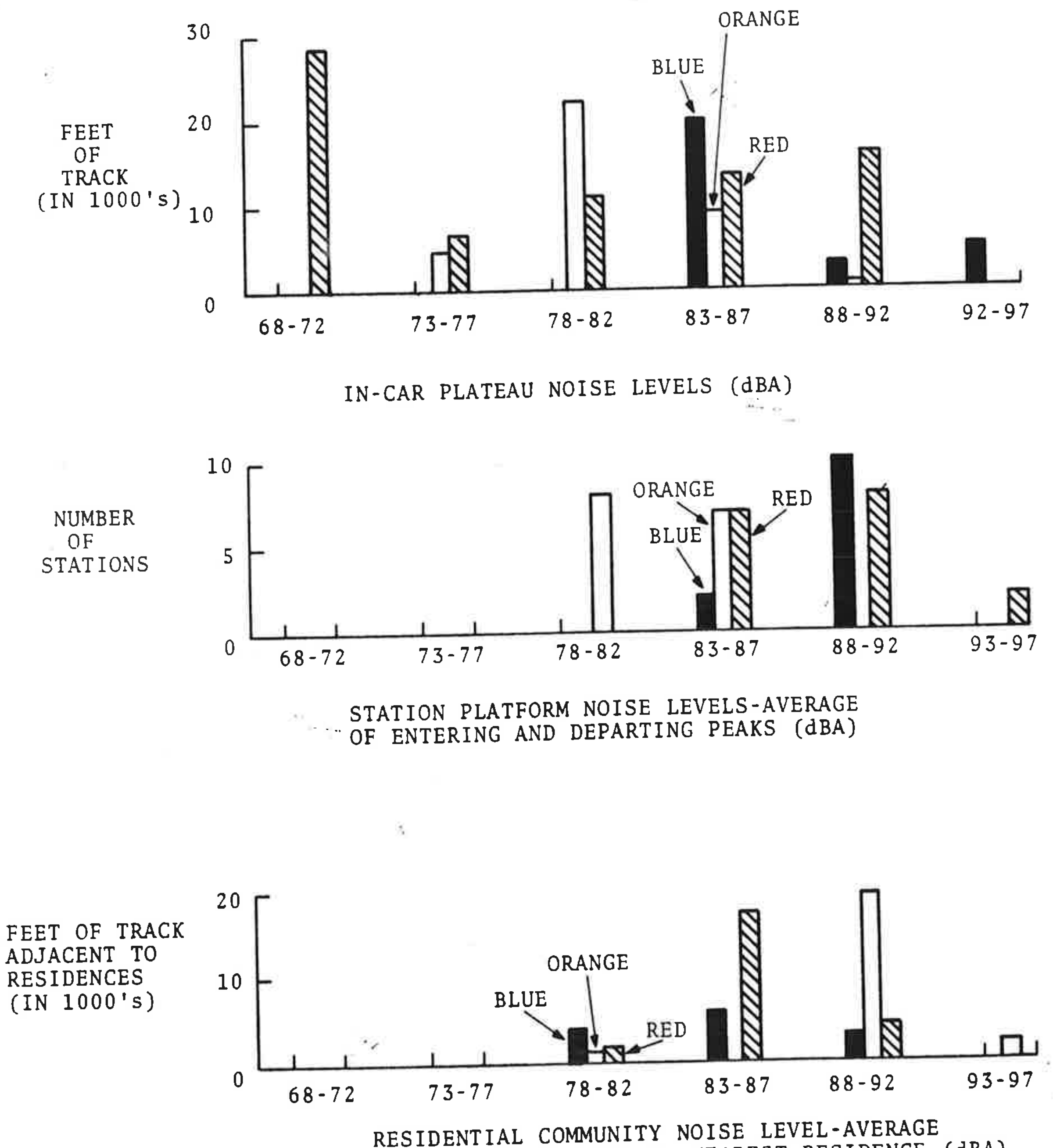

Figure 4-1 Summary of MBTA Noise Status

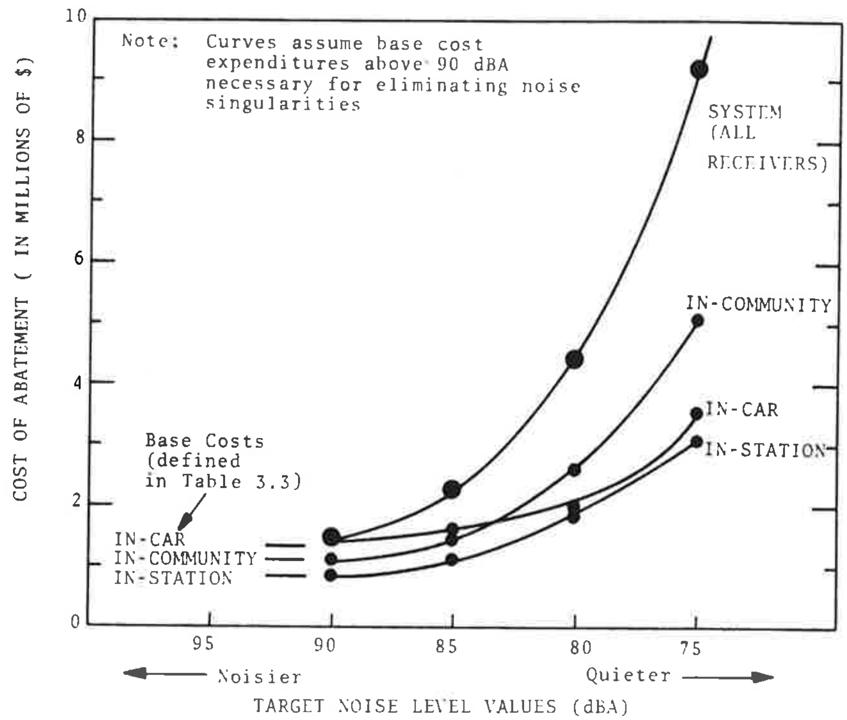

Figure 4-2 Cost of Abating the MBTA Rapid Transit System to a Specified Level (dBA) at each Receiver

(c) Examples of community noise environments are given in Table 4.1.* These are averages of daytime or night-time outdoor noise levels, in various city locations (e.g., downtown Los Angeles, tenement in New York, apartments adjacent to freeways, urban shopping centers, etc.). Also given in this table are average noise levels for various urban and suburban areas. The "residual noise level" is approximately the level exceeded 90% of the time, while the "median noise level" is the level exceeded 50% of the time.

(d) An important reference is provided also by the noise levels measured inside and outside the BART Prototype Car 107. These levels are summarized in Table 4.2.**

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*Reference 15, Appendix C

**Reference 18, Appendix C

TABLE 4-1 COMPARISON OF AVERAGE DAYTIME AND NIGHTTIME OUTDOOR NOISE LEVELS IN CITY AND DETACHED HOUSING RESIDENTIAL AREAS

	Average Daytime (7 AM-7PM)			Average Nighttime (10PM-7AM)			Difference Between Day and Night	
General Category	Range dB(A)	Arithmetic Mean dB(A)	Standard Deviation dB	Range dB(A)	Arithmetic Mean dB(A)	Standard Deviation dB	Average Difference dB	Standard Deviation of Difference dB
Residual Noise Level (L_{90})								
City (4 Locations)	61 to 77	69.1	6.1	51 to 69	60.8	6.3	8.3	2.1
Suburban and Urban Detached Housing Residential (11 Locations)	38 to 53	45.6	4.6	35 to 46	39.8	4.1	5.8	3.6
Median Noise Level (L_{50})								
City (4 Locations)	64 to 80	73.0	6.23	55 to 75	65.5	7.2	7.5	3.0
Suburban and Urban Detached Housing Residential (11 Locations)	44 to 59	50.9	4.1	38 to 50	44.2	4.3	6.7	2.6

Data from "Report to the President and Congress on Noise", U.S. Environmental Protection Agency February 1972.

Note: Data are averages of hourly values during indicated period.

TABLE 4-2 SUMMARY OF SOUND LEVELS IN dBA FROM BART CAR 107 NOISE TESTS ON BALLAST AND TIX TARGET TRACK

	Standard Wheel-Standard Rail	Standard Wheel-Ground Rail	Standard Wheel w/Glass Fiber-Ground Rail	Acousta Flex Wheel-Ground Rail	Damped Wheel-Ground Rail	Damped Wheel w/Glass Fiber Ground Rail
Interior Noise Level @ 60 MPH						
X-END	80	76	72	73	76	72
Y-END	80	75	73	73	73	72
CENTER	75	70	68	69	70	69
Exterior Noise Level @ 60 Mph						
25 FT	92	83	83	83	83	82
50 FT	87	79	79	79	80	79
Interior Noise Level @ 80 MPH						
X-END	84	79	76	79	80	76
Y-END	83	79	76	79	79	77
CENTER	78	75	71	74	73	72
Exterior Noise Level @ 80 MPH						
25 FT	95	88	87	88	87	86
50 FT	90	84	83	83	84	83

Data from "BART Prototype Car 107 Noise Tests", Wilson, Ihrig and Associates, 1971

(e) An additional reference should be noted, namely, the Guidelines of the Institute for Rapid Transit for new rapid transit systems. These noise limit guidelines may be summarized as follows:

Vehicle Interior	
In open, at maximum speed	68 to 72dBA
In tunnels, at maximum speed	78dBA
Wayside Noise @ 50 Ft	
Two-car train @ 60 m.p.h.	82dBA
Underground Stations	80 to 85dBA
Above Ground Stations	70 to 75 dBA

The message that appears so far is that the rapid transit system under consideration here is "noisy" and that the excessive noise appears to be generally 10 to 15 dBA above the existing or recommended noise levels of new rapid transit systems. This may be considered as one possible answer to the question "how much abatement?" Other possible answers might be provided by regulations, by standards of acoustical comfort for the rider, or by criteria for acceptable noise impact to the wayside community.

There are neither current nor projected regulations regarding noise generated in or around rapid transit rail systems. The only regulation in existence is the Occupational Safety & Health Act of 1970. This act provides essentially for the protection of working individuals against noise-induced hearing damage. The criterion may be stated simply by requiring the sum of relative exposures, SUM (C_n/T_n), to be lower than one. In the aforementioned sum, the numerator of each fraction is the total time of actual exposure to a specified noise level, while the denominator is the allowed total time of exposure to this level. The maximum allowed exposure times are given below:

90 dBA	8 hours daily
92	6 hours
95	4
97	3
100	2
102	1.5
105	1.0
110	0.5
115	0.25 hours or less

A comparison of this criterion with the potential exposure of employees to MBTA noise, (see Figure 4.1), shows that the criterion is satisfied but only by a relatively narrow margin. In fact, less permissive criteria, which are presently contemplated, might not be satisfied in certain cases. This refers naturally to employees or other individuals exposed to the rapid transit noise for time intervals much longer than the duration of a ride. The rider and the wayside community are receiving exposures which although not significant from the viewpoint of hearing damage, might cause task interference or outright annoyance.

For the rider a very important instance of interference and annoyance is the interference with speech communication that results from noise, especially during the ride. Figure 4.3 summarizes the relation between interfering noise and the possibilities for speech communication as a function of talker-to-listener distance in feet. It may be seen, for example, that normal speech communication at distances greater than 2 feet requires the interfering noise level to be lower than about 75 dBA.

The problem considered now is that of community annoyance by and reaction to the intrusive noise of rapid transit pass-bys. There is a large variety of community noise rating schemes in the literature. Many are specifically concerned with a predominant source of transportation related noise, but there is no specific scheme for rating annoyance caused by rapid transit vehicle pass-by noise. However, the U.S. Environmental Protection Agency has

adopted a method for use in its 1972 report to the President and Congress.* The method under consideration is designated as the Community Noise Equivalent Level (CNEL). The use of this rating method should not be interpreted as an endorsement by the U.S. EPA since neither CNEL nor any other rating method has been sufficiently validated to determine their adequacy in predicting present and future community reaction to noise.

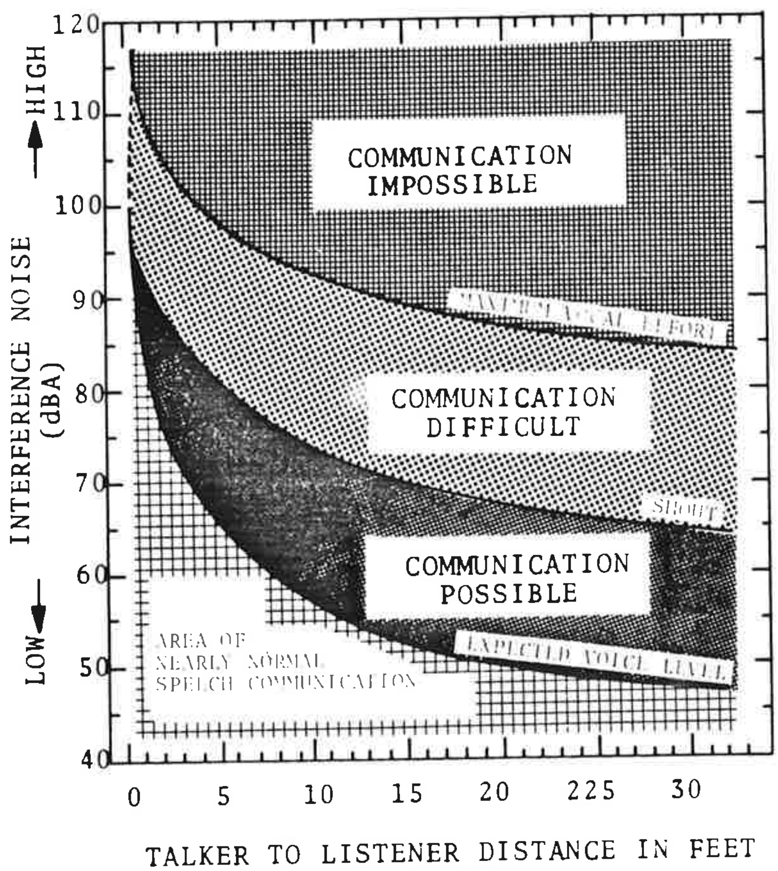


Figure 4-3 Speech Interference Level

*See Reference 15, Appendix C

This rating, when normalized by a procedure to be described later in this section, gives a measure of the community reaction to intrusive noises, regardless of origin. For the specific case of repeated and frequent noise intrusions encountered in wayside communities, simple and approximate algorithms are available.*

CNEL may be obtained from

$$CNEL = SENEL + 10 \log N_c - 49.4 \text{ dB}$$

where SENEL is the Single Event Noise Exposure Level and N_c is given by

$$N_c = N_d + 3N_e + 10N_n$$

N_c is the total effective number of train pass-by events. The three terms in this expression are:

N_d = The number of train pass-by events during the day (0700 to 1900 hrs).

N_e = The number of train pass-by events during the evening (1900 to 2200 hrs), weighted by a factor of three.

N_n = The number of train pass-by events during the night (2200 to 0700 hrs), weighted by a factor of 10.

The weighting factors reflect more annoyance during the evening hours and even more so during the night hours. SENEL is given approximately by the following algorithm.*

$$SENEL = NL_{max} + 10 \log_{10} t_{ea} \text{ dB}$$

where

NL_{max} = maximum noise level as observed on the A scale of a standard sound level meter

*See Reference 20, Appendix C

and

t_{ea} = effective time duration of the noise level (on A scale) in seconds

The effective duration is approximately equal to 1/2 of the duration for which the noise level is within 10dB of the maximum noise level.

For the sake of generality the following assumptions are made in obtaining numerical results. Two cases are assumed for the maximum noise level of a train pass-by event.

- Case 1 NL_{max} = 90dBA
- Case 2 NL_{max} = 75dBA

It is further assumed that five seconds is a typical train pass-by duration (duration of noise with a level within 10 dBA of the maximum level). Furthermore, values must be assigned to the number of operations during the day, evening and night. An inspection of MBTA schedules and headway reveals that in a typical situation, the numbers of (two-way) pass-bys are about 288, 30 and 32 during the day, evening and night hours, as defined above. Essentially, these numbers correspond to headways of 5, 12, and 15 minutes for the day, evening and night periods, with no operations between 0030 and 0530 hours.

The CNEL values may be calculated now from the algorithms presented above. These values are 73 and 58 dB for Cases 1 and 2 respectively. Incidently, for the reader who is familiar with the Noise Exposure Forecast (NEF) method, used in airport noise forecasts, the difference between CNEL and NEF is approximately constant at 35 $\pm$ 2dB. Further corrections must be made to the quoted numerical values of CNEL in order to obtain the so called Normalized Community Noise Equivalent Level. The corrections suggested in Reference 15, Appendix C, are reproduced here in Table 4.3. As may be seen they refer to seasonal corrections, corrections for outdoor residual noise level, corrections for

TABLE 4-3 CORRECTIONS TO CNEL TO OBTAIN NORMALIZED CNEL

Type of Correction	Description	Amount of Correction to be Added to Measured CNEL in dB
Seasonal Correction	Summer (or year-round operation)	0
	Winter only (or windows always closed)	-5
Correction for Outdoor Residual Noise Level	Quiet suburban or rural community (remote from large cities and from industrial activity and trucking)	+10
	Normal suburban community (not located near industrial activity)	+5
	Urban residential community (not immediately adjacent to heavily traveled roads and industrial areas)	0
	Noisy urban residential community (near relatively busy roads or industrial areas)	-5
	Very noisy urban residential community	-10
Correction for Previous Exposure & Community Attitudes	No prior experience with the intruding noise	+5
	Community has had some previous exposure to intruding noise but little effort is being made to control the noise. This correction may also be applied in a situation where the community has not been exposed to the noise previously, but the people are aware that bona fide efforts are being made to control the noise.	0
	Community has had considerable previous exposure to the intruding noise and the noise maker's relations with the community are good	-5
	Community aware that operation causing noise is very necessary and it will not continue indefinitely. This correction can be applied for an operation of limited duration and under emergency circumstances.	-10
Pure Tone or Impulse	No pure tone or impulsive character	0
	Pure tone or impulsive character present	+5

previous exposure to the intruding noise and community attitudes, and to other minor corrections. For the problem under consideration here i.e., urban rail rapid transit in operation, the following adjustments are believed relevant.

Description of Correction	Amount of Correction
Year-Round Operation	C dB
Urban Residential Community	0 dB
Community has considerable previous exposure to the intruding noise	-5 dB
No Pure Tone or Impulsive Character	0 dB
Total Correction	-5 dB

Accordingly, the normalized CNEL is given by:

	Maximum Noise Level During Train Pass-by	Normalized CNEL
Case 1	90 dBA	68 dB
Case 2	75 dBA	53 dB

The normalized CNEL can now be related to various expected community reactions. This may be done with the help of Figure 4.4, taken from Reference 15, Appendix C. This is essentially a calibration curve that the U.S. Environmental Protection Agency is considering. It is based on the results of 55 case histories, covering a very large variety of community reactions to various intruding noises.

As may be seen, Case 1 with a normalized CNEL value of 68 corresponds to community reactions stronger than "widespread complaints". An abatement of the maximum noise level (during a train pass-by by 15 dBA, which corresponds to Case 2 with a normalized CNEL of 53 dB, is expected to eliminate the possibility of complaints. Note that the range 75 to 90 dBA for maximum noise levels is the dominant range encountered in this report (see Figures 4.1 and 4.2).

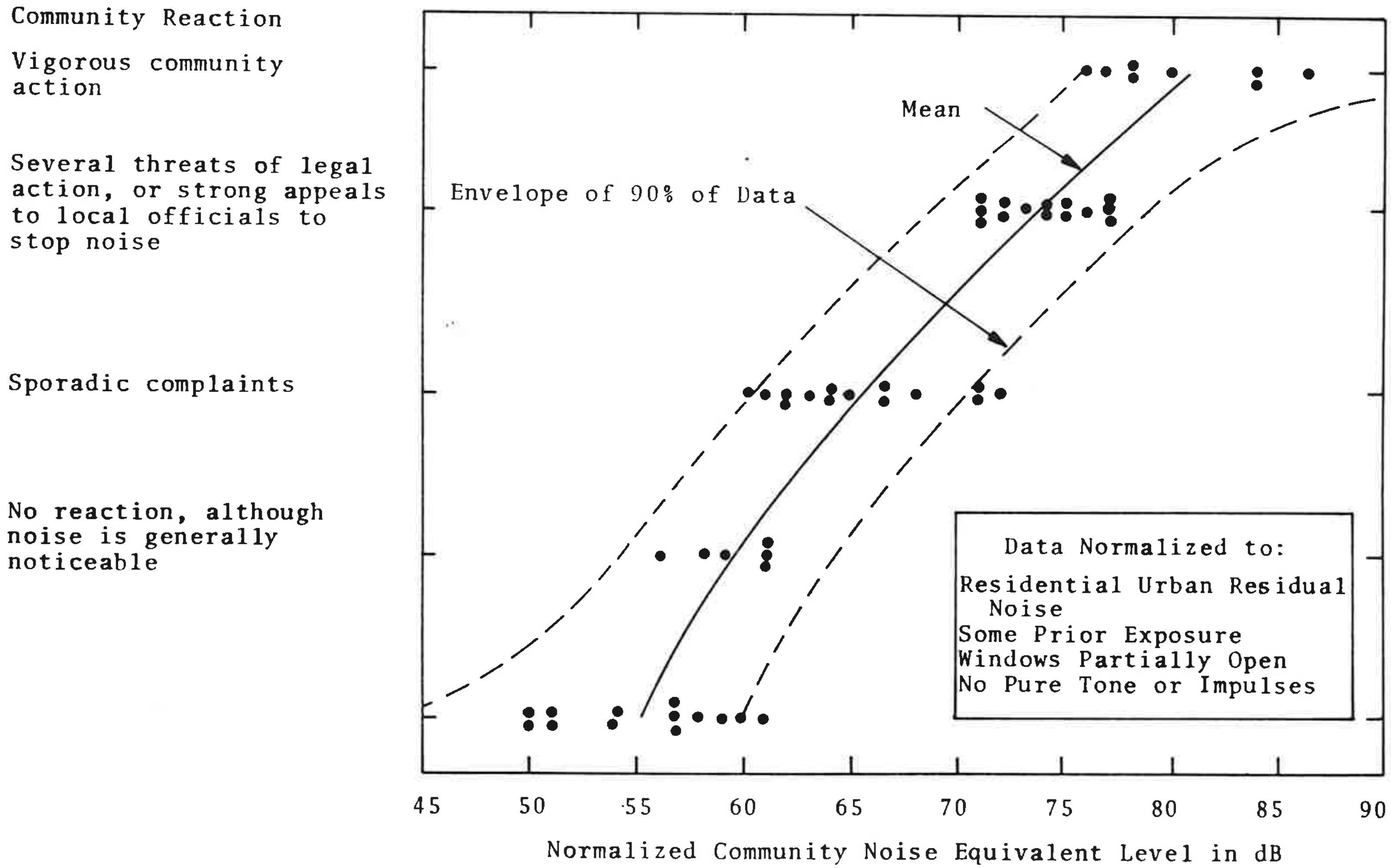


Figure 4-4 Community Reaction to Intrusive Noises of Many Types as a Function of the Normalized Community Noise Equivalent Level

5.0 REMARKS AND RECOMMENDATIONS

A general approach has been developed for the assessment of noise, noise abatement requirements, and associated costs, as a function of desired upper limit of noise. The approach is applicable to all urban rail rapid transit systems. A pilot application of the approach has been made to the MBTA. Unless otherwise noted, the following concluding remarks and recommendations are generally applicable:

1. The dominant range of MBTA noise (in-car, in stations, and in wayside communities) is 75 to 90 dBA, with most of the system exposed to the upper third of this range. This is not unusual for rapid transit systems in the United States. However, the MBTA is considered to be quite "noisy".

2. Based on guidelines and other material proposed by Federal and private organizations concerned with environmental quality, the present upper noise limit (90 dBA) appears to be unacceptable. The lower limit (75 dBA) is generally more acceptable.

3. The assessment of noise abatement requirements and the cost of abatement were carried out for the range of 75 to 90 dBA. It has been determined that:

   a. Technology exists for reducing the noise levels of rapid transit systems by 15 to 20 dBA.

   b. Based on the MBTA application, the normalized cost of noise abatement are approximately $2.50, $5.00 and $10.00 per linear foot of double track per dBA, for reduction of noise in cars, in wayside communities and in stations respectively. These normalized costs have been found relatively insensitive to the desired upper limit of noise or to the portion of system requiring abatement.

c. For the specific case of the MBTA Blue, Red and Orange Lines, noise abatement to a level of 75 dBA at all receivers would cost about $10 million. This is the cost for materials and labor, excluding engineering and overhead.

d. Approximately 15% of the cost is assigned to the elimination of signular noise, (wheel squeal, noisy door operation, unmuffled air brakes), by straightforward techniques. Any noise abatement program should start with a reduction of the aforementioned singular noise which is particularly annoying, in view of its tonal content and/or its impulsive character.

4. Two very essential parts of the approach used in this report are:

   a. The formulation of "scenarios" which are essentially the identification of the contributions made by each noise source and each propagation path to an observed overall noise level, in each noise control class of the system.

   b. The application of information regarding the noise reduction potential and the cost of components and techniques available for noise abatement.

Existing experimental data and engineering judgement were used extensively in the above. Although these were found adequate for report purposes, the engineering tasks of actual noise abatement will require more reliable support. Such support should be obtained through experimental verification of the most important details in the "scenarios" and of the noise reduction potential of the leading noise abatement techniques and components.

5. The identification of optimal (minimal cost) noise abatement strategies was found to be straightforward but quite cumbersome without computer assistance. For this reason a programmable algorithm is recommended, see Appendix A.

6. A review of documents from several Federal and private organizations, concerned with improvements of environmental quality, reveals that there are neither current nor projected laws, regulations or any standards which set limits to the noise generated by rapid transit systems. The Occupational Safety and Health Act of 1970 is an exception in the sense that it deals with the extreme situations of potential hearing damage.

7. A cursory application of the criteria of the aforementioned Act to MBTA shows that the criteria are satisfied by a narrow margin. This margin might become narrower, in view of recent proposals to reformulate the criteria with lower permissible exposure levels.

8. The development of a framework is recommended for the reasoned establishment of priorities, schedules, and allocation of resources for noise abatement in urban rail rapid transit systems. This is necessary because of:

   a. The wide range of noise climates.

   b. The variety of exposures for various receivers in various parts of the system.

   c. The absence of standards and regulations.

   d. The substantial cost of noise abatement.

9. The importance of the above recommendation becomes evident when the cost for noise abatement on all United States rapid transit systems is considered. Conclusion 3c summarizes the basic cost for a specified noise abatement in the MBTA at an estimated $10 million. If the assumption is made that most U.S. rapid transit systems require comparable treatment, then the corresponding cost will amount to many hundred million dollars.

APPENDIX A
ALGORITHM FOR MINIMIZING COST TO REDUCE RAPID TRANSIT NOISE

The algorithm for Cost-Abatement Analysis presented here, will achieve at least cost a desired set of noise levels along a rapid transit line. The algorithm is given in the form of a simplified logic flow diagram, the main purpose of which is to convey to the reader the essential features of the digital computer program presently being developed by TSC. Although the program is designed specifically for rapid transit systems, the approach is generally applicable to minimize noise control costs on any vehicle-guideway transportation system. An equivalent but less formal procedure (using pencil, paper, and programmable desk calculator) was followed in the MBTA pilot study. There, all scenarios were assigned identical desired levels. The present algorithm permits each scenario to have a separately assigned desired level.

ALGORITHM FOR MINIMIZING COST TO REDUCE RAPID TRANSIT NOISE

For each principal receiver (community, rider, station patron,) do the following:

↓

Measure noise on line.

↓

Divide line into segments.

↓

Aggregate acoustically similar segments into mutually exclusive groups.

↓

From existing data, new data, and engineering judgement put together a source-path scenario for each such group,
consisting of: contribution from each source via each path,
total level, desired level,
total line footage in group

↓

Comment: If there are S scenarios, L line noise reduction techniques and C car reduction techniques then there are (SL + C)! different possible combinations of techniques and locations along the line for applying

them. For S=11, L=10 and C=9 this is 119! or $4.15X10^{198}$ combinations. The most straightforward way to proceed is to simply calculate the total cost and new scenario levels for each combination over the whole line, and save at any point in the calculation, the cheapest (or several cheapest) combination(s) which achieve the desired level (s).

An alternative is to recognize that for any combination of car techniques the cheapest overall cost will occur when each of the scenario costs is minimized. This reduces the problem to approximately L! x S x C! or 11! x 9! or $1.45X10^{13}$. Since logarithmic addition is time consuming we reduce this number further by eliminating some of the obviously inappropriate combinations:
a) those that can't possibly reduce levels sufficiently, and b) those that will cost more than combinations which already have been determined to satisfy the required levels.

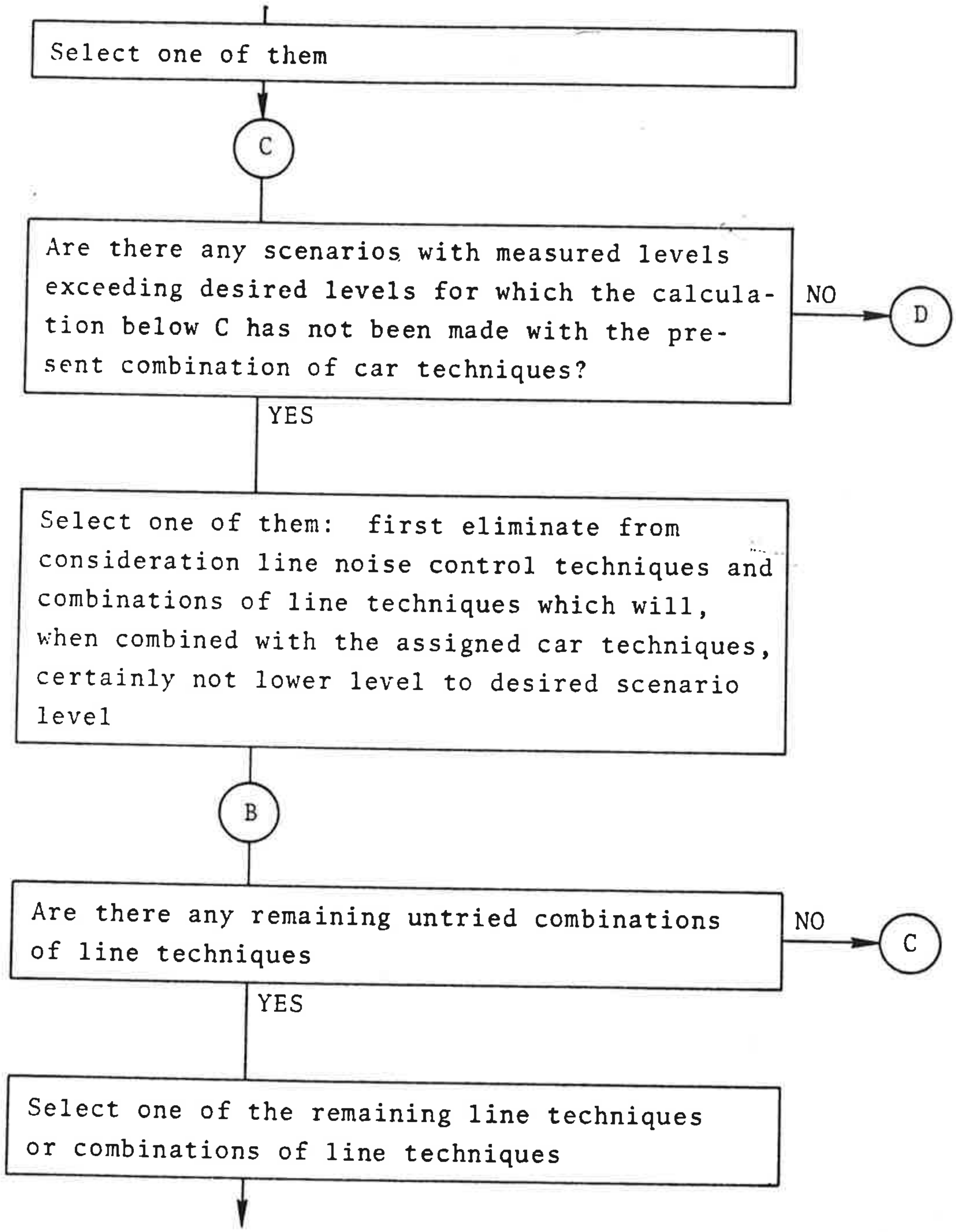
Determine all combinations of car techniques (include using no car techniques)

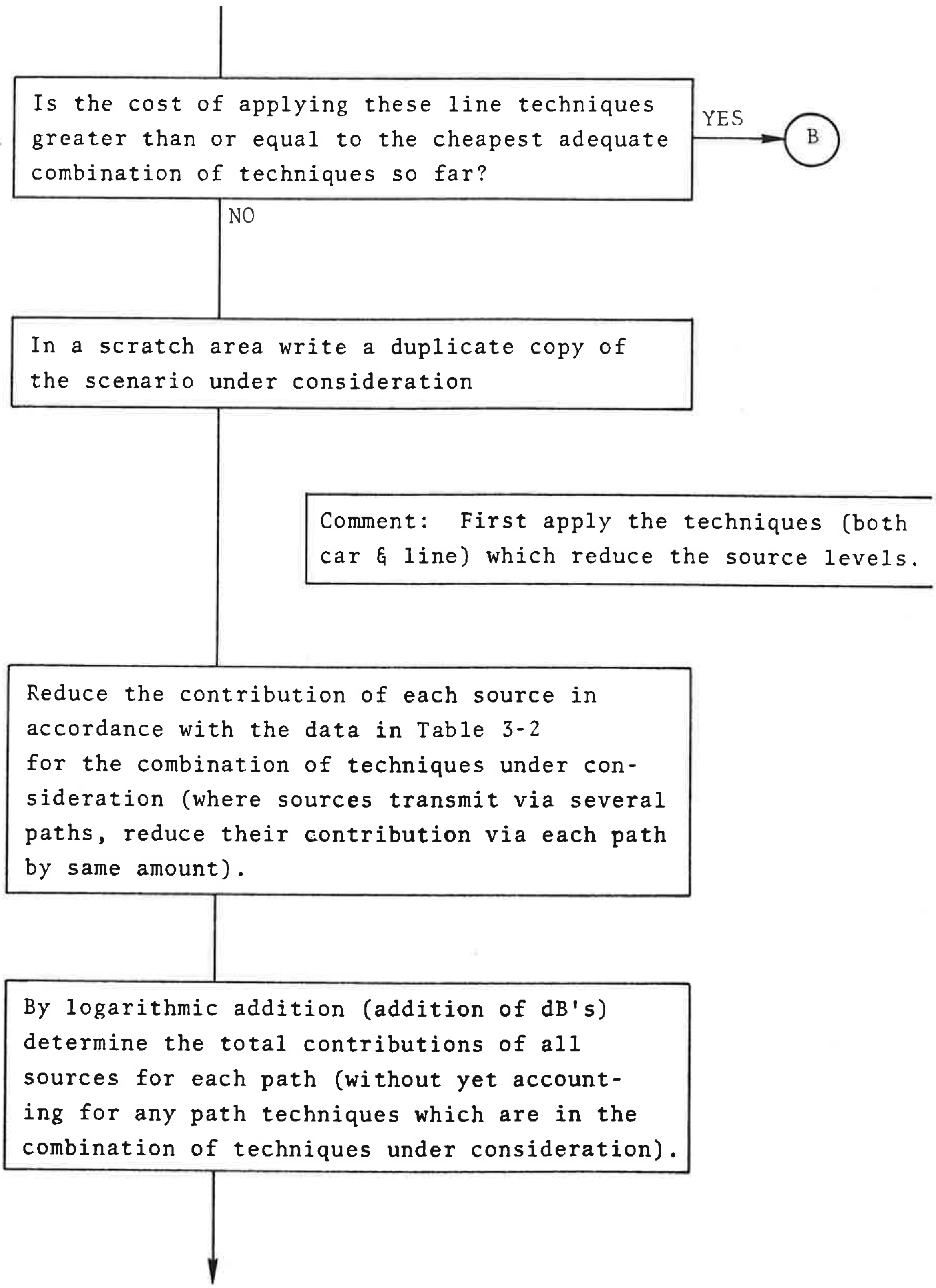
(A)

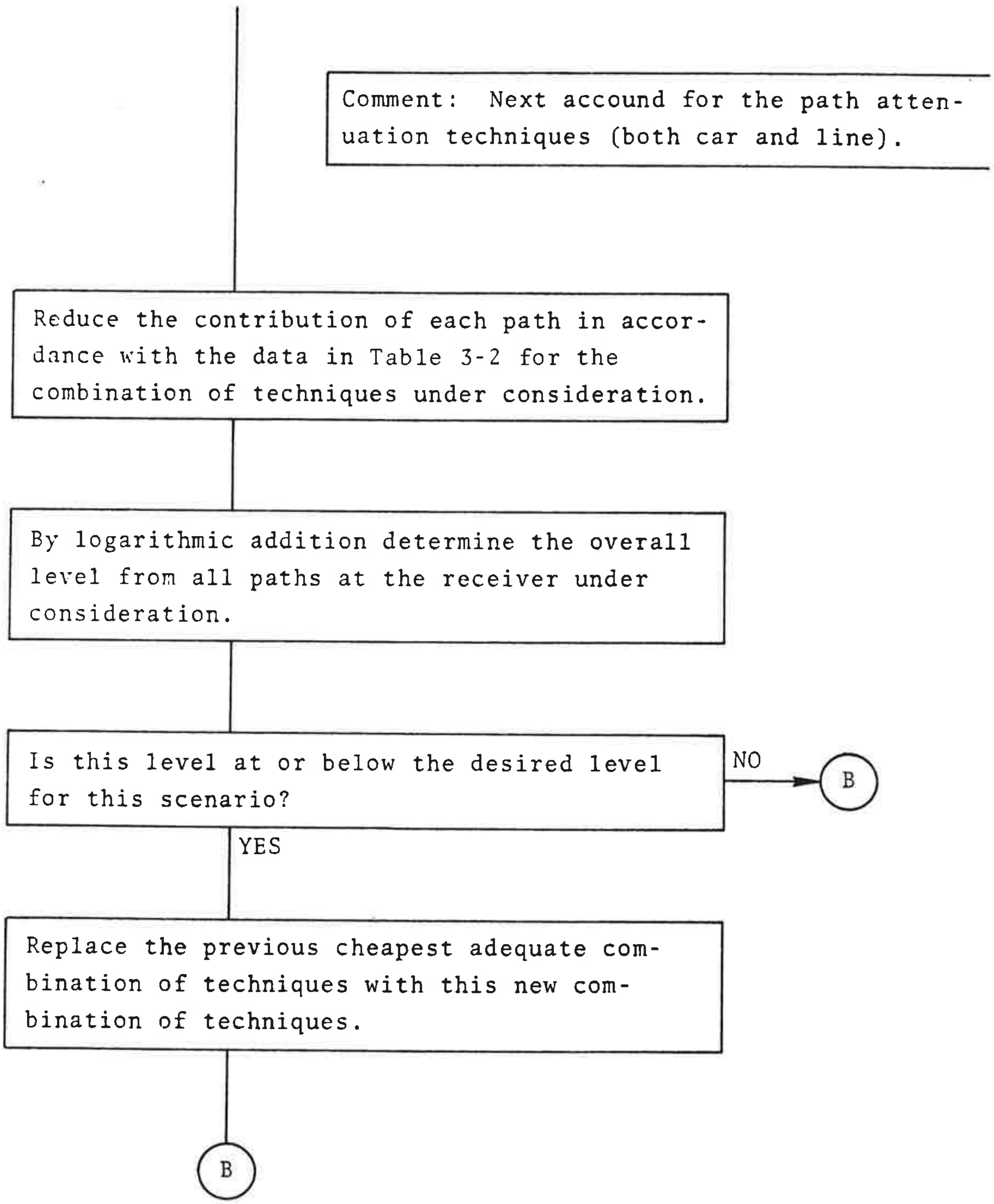
Are there any combinations of car techniques for which line minimization has not been performed (C to e)

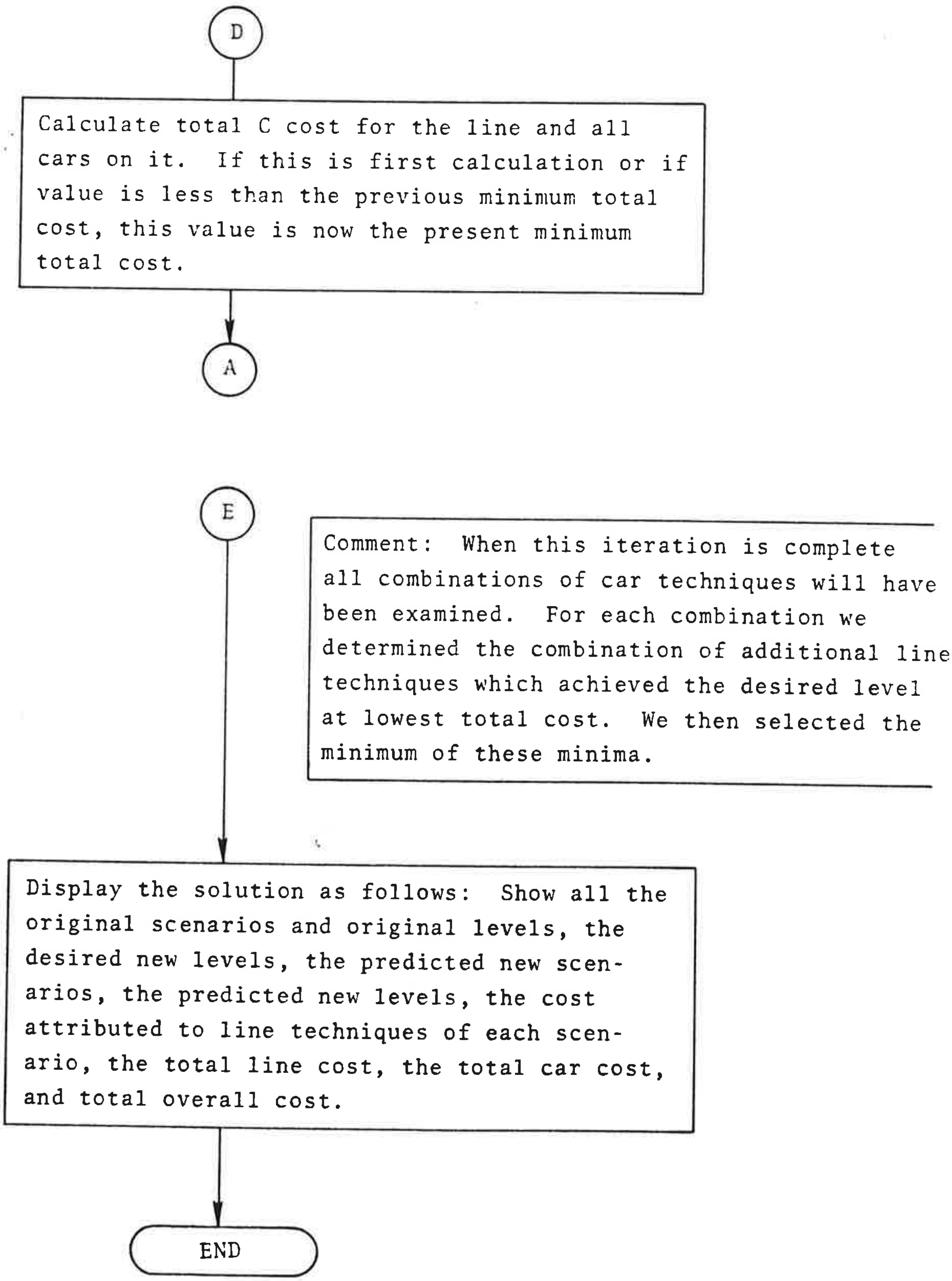
NO → (E)

YES


Select one of them
C
Are there any scenarios with measured levels exceeding desired levels for which the calculation below C has not been made with the present combination of car techniques?
NO
D
YES
Select one of them: first eliminate from consideration line noise control techniques and combinations of line techniques which will, when combined with the assigned car techniques, certainly not lower level to desired scenario level
B
Are there any remaining untried combinations of line techniques
NO
C
YES
Select one of the remaining line techniques or combinations of line techniques


Is the cost of applying these line techniques greater than or equal to the cheapest adequate combination of techniques so far?
YES
B
NO
In a scratch area write a duplicate copy of the scenario under consideration
Comment: First apply the techniques (both car & line) which reduce the source levels.
Reduce the contribution of each source in accordance with the data in Table 3-2 for the combination of techniques under consideration (where sources transmit via several paths, reduce their contribution via each path by same amount).
By logarithmic addition (addition of dB's) determine the total contributions of all sources for each path (without yet accounting for any path techniques which are in the combination of techniques under consideration).


Comment: Next accound for the path attenuation techniques (both car and line).
Reduce the contribution of each path in accordance with the data in Table 3-2 for the combination of techniques under consideration.
By logarithmic addition determine the overall level from all paths at the receiver under consideration.
Is this level at or below the desired level for this scenario?
NO
B
YES
Replace the previous cheapest adequate combination of techniques with this new combination of techniques.
B


D
Calculate total C cost for the line and all cars on it. If this is first calculation or if value is less than the previous minimum total cost, this value is now the present minimum total cost.
A
E
Comment: When this iteration is complete all combinations of car techniques will have been examined. For each combination we determined the combination of additional line techniques which achieved the desired level at lowest total cost. We then selected the minimum of these minima.
Display the solution as follows: Show all the original scenarios and original levels, the desired new levels, the predicted new scenarios, the predicted new levels, the cost attributed to line techniques of each scenario, the total line cost, the total car cost, and total overall cost.
END

APPENDIX B
MBTA SCENARIOS

A scenario is the identification of the contributions made by each noise source and each propagation path to an observed overall noise level.

TABLE B-1 SCENARIOS FOR IN-CAR NOISE LEVELS

[illegible]	TOTAL [illegible]	[illegible]	[illegible]*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	85	[illegible]	[illegible]		87	[illegible]	[illegible]	[illegible]	71	[illegible]	[illegible]		[illegible]
		[illegible]	[illegible]		[illegible]	67	[illegible]	56	71	[illegible]	-		
		78	[illegible]		76	71	71	54	71	-	-		BRIDGE
		72	[illegible]		[illegible]	64	64	56	-	-	-		
		80	64		75	72	72	64	-	-	-		
		65	P5		-	-	-	-	-	-	[illegible]		
[illegible]	80	80	ML		78	71	71	60	60	68	65		[illegible]
		[illegible]	[illegible]		74	62	62	45	60	68	-		[illegible]
		[illegible]	[illegible]		71	66	66	49	50	-	-		[illegible]
		[illegible]	63		63	55	55	51	-	-	-		
		[illegible]	[illegible]		73	67	67	59	-	-			
		65	P5		-	-	-	-	-	-	65		
45**	80	80	ML	73	76	70	70	54	65	68	65		[illegible]
		79	P1	69	72	[illegible]	68	43	64	68	-		
		[illegible]	P2	71	74	62	69	52	50	-	-		
		64	P3	58	61	55	55	47	-	-	-		
		65	P5	-	-	-	-	-	-	-	65		

**Scenario [illegible] is for the Silverbirds running on the Red Line scenario 2 section

* [illegible] PATHS

P1 = Pa+Pf
P2 = Pc+Pd+Pb
P3 = Pe+Pd+Pb
P4 = Pc+Pd+Pb
P5 = Pf

Where
Pa = Structureborne path
Pb = interior reverberation
Pc = exterior reverberation
Pd = car body transmission loss
Pe = direct radiation to car exterior
Pf = direct field, car interior
P[illegible] = secondary radiation to car exterior

TABLE B-2 SCENARIOS FOR STATION NOISE

SCENARIO	TOTAL*	PATH	RAIL JOINTS*	RAIL ROUGHNESS*	WHEEL ROUGH*	CONSTRUCTION
S1		P1	80	74	74	Tunnel, Bolted Joints
		P2	93	87	87	
		P3	80	74	74	
	95	Total	93	87	87	
S2& S3		P1	75	69	69	Tunnel, Bolted Joints
		P2	88	82	82	
		P3	75	69	69	
	90	Total	88	82	82	
S4		P1	83	77	77	Grade Level
		P2	86	80	80	
		P3	83	77	77	
	90	Total	89	83	83	
S5& S6		P1	70	64	64	Tunnel, Bolted Joints
		P2	83	77	77	
		P3	70	64	64	
	85	Total	83	77	77	
S7& S8		P1	74	68	68	Grade Level
		P2	82	76	76	
		P3	74	68	68	
	85	Total	83	77	77	
S9 S10, S11		P1	76	70	70	Elevated
		P2	80	74	74	
		P3	79	73	73	
	85	Total	83	77	77	
S12, S13, S14	80	P1	71	65	65	Elevated
		P2	75	69	69	
		P3	74	68	68	
		Total	78	72	72	

* dBA

PATH DEFINITIONS

P1 = Direct Radiation From Wheel-Rail To Listener

P2 = Station Reverberation

P3 = Secondary Radiation From Structure

TABLE B-3 SCENARIOS FOR RESIDENTIAL WAYSIDE PASS-BY NOISE

SCENARIO	AVG PASSBY LEVEL	PATH CONTRIB.	PATH	WHEEL FLATS	RAIL JOINTS	RAIL ROUGH	WHEEL ROUGH	POWER PICKUP	PROPUL-SION	AUX (MECH)	AUX (AERO)	CONSTRUCTION
C1	90	90	P6		88	82	82	66	75	60	-	Jointed, Grade
C2	85	85	P6		83	77	77	61	70	60	-	Jointed, Grade
C3	80	80	P6		78	72	72	56	65	60		Jointed, Grade
C4	95	89 94	P6 P7		87 92	81 86	81 86	65 -	74 -	60 -	- -	Jointed, Elevated
C5	90	84 89	P6 P7		82 87	76 81	76 81	60 -	69 -	60 -	- -	Jointed, Elevated
C6	80	74 79	P6 P7		72 77	66 71	66 71	50 -	59 -	60 -	- -	Jointed, Elevated
C7	85	85	P6	82		79	79	66	70	60	-	Welded, Grade
C8	85	82 82	P6 P7	79 79	- -	76 76	76 76	66 -	70 -	60 -	-	Welded, Elevated

PATH DEFINITIONS

P6 = Direct Airborne Path From Under Car To Wayside Community

P7 = Structureborne Path Into Elevated Structure, Plus Airborne Path To Community

APPENDIX C

REFERENCES

The following references were used to provide the background data from which Table 3.2 was derived.

1. "Noise Generated by Subways Aboveground and in Stations", E.K. Bender, M. Heckl, BBN Technical Report Contract No. DOT-OS-A9-040, Jan. 1970.

2. "Noise Control in the BART System, Final Report", V. Salmon, S.K. Oleson, SRI, July 1966.

3. "Diablo Test Track Noise and Vibration Measurements", Wilson, Ihrig, and Associates, June 1967.

4. "Smooth Ground Rail Noise and Vibration Measurements", Diablo Test Track, Wilson, Ihrig, and Assoc., Sept. 1968.

5. "Noise and Vibration Characteristics of High Speed Transit Vehciles", Wilson, Ihrig, and Assoc., June 1971.

6. "Noise and Vibration Control", Toronto Transit Commission Report RD 109, May 1967.

7. "Viscoelastic Damping for Rapid Transit Structures", F. Kirschner, V. Salmon, S. Oleson, 5 Congres International D'Acoustique, Paper No. F31, Sept. 1965.

8. "A Study of the Magnitude of Transportation Noise Generation and Potential Abatement, Volume V - Train System Noise", Serendipity, Nov. 1970.

9. "Study on Noise Reduction in the Vehicle of Underground Railway by Acoustical Treatment of the Wall of Tunnel", Ishu and Kayamaki, Aug. 1968.

10. "Comparison of Noise and Vibration Levels in Rapid Transit Vehcile Systems", E. Davis, et al., Operations Research Inc., April 1964.

11. Private Communication with members of Bolt Beranck and Newman, Inc. , Toronto Transit Commission.

Information related to the MBTA System was derived from items 12-14:

12. "Subway Environmental Survey - MBTA", De Leuw, Cather & Co., Technical Report No. UMTA-DC-MTD-7-71-20, Sept. 1971.

13. MBTA Pamphlets and private communications with members of the MBTA.

14. MBTA Rapid Transit System (Red Line) Wayside and In-Car Noise and Vibration Level Measurements - E.J. Rickley and R. W. Quinn, May 1972, DOT-TSC-OST-72-31

Further references used in the compilation of this report:

15. "Report to the President and Congress on Noise", by the U.S. Environmental Protection Agency, February 1972.

16. "HUD Noise Assessment Guidelines", Technical Background, U.S. Department of Housing and Urban Development, 1972.

17. "Guidelines and Principles for Design of Rapid Transit Facilities", Section 7, "Acoustics", to be published by the Institute for Rapid Transit.

18. "BARTD Prototype Car 107 Noise Tests", Wilson, Ihrig and Associated, 1971.

19. "Transportation Noise" U.S. Environmental Protection Agency, NTID 300.13, December 1971.

20. "Community Noise" U.S. Environmental Protection Agency, NTID 300.3, December 1971.

APPENDIX D

DEFINITIONS

DEFINITIONS

Ambient Noise - The average background sound pressure level in the absence of unique noise events under specific study.

A-Weighting Network - A circuit designed to reduce the sensitivity of a sound level meter below 1 kHz so as to approximate the sensitivity of the human ear.

A-Weighted Sound Level (dBA) - The output, in decibels, of a sound level meter which contains an A-weighting filter network.

Decibel (dB) - The most commonly used unit to express sound level relative to a reference sound pressure of 20 micronewtons per square meter (the human hearing threshold). Quantitatively the sound pressure level in decibels is 20 log (P/.00002) where P is the root-mean-square sound pressure.

Hunting - A lateral instability of the trucks on the rails which may result in sway of the vehicle body and impact of the wheel flange on the rail head.

Impact (mechanical) - A dynamic force of short duration due to a geometric discontinuity of a wheel or rail in rolling contact.

Noise (acoustic) - Any erratic, unwanted, random sound within the normal frequency limits for hearing.

Noise Climate - The collective description of the sound pressure levels of the transit system as a whole catalogued in terms of values at the receivers.

Noise Exposure - The sound pressure level which is typical at a certain location or to which a given receiver is subjected over a period of time.

Noise Level and Sound Level - Refer to the A-Weighted Sound Level.

Noise Path - The physical route taken by the noise traveling from a source to a receiver.

Noise Source - The physical entity which produces sound energy.

Passby - The total event of a train approaching passing and receding from a fixed point of observation.

Roar - The noise (not including impact and squeal) of wheels running on track.

Receivers - Any sensitive subject exposed to rapid transit system noise. The three categories used in the report are riders in the car, patrons on the platform and wayside residents.

Scenarios - The breakdown of the source - path contributions to the overall noise level at each receiver on acoustically similar track sections.

Singularities - Brief high intensity sounds which are particularly annoying due to either their startle effect or thier pure tone content (such as wheel screech, door slam, brake air vent hiss).

Wheel Squeal - A high frequency noise with pure tone content (sometimes several frequencies simultaneously) due to resonant vibrations.