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NOISE ASSESSMENT AND ABATEMENT IN RAPID TRANSIT SYSTEMS

Report on the MBTA Pilot Study

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16. Abstract

As Systems Manager for the Urban Rail Supporting Technology Program sponsored by the Rail Programs Branch of the Urban Mass Transportation Administration, the Transportation Systems Center is conducting an effort in Urban Rail Noise Abatement. A portion of this effort, described herein, is concerned with the assessment of noise and of the potential for noise abatement on existing U.S. transit properties. A methodology is described for assessing the noise climate and for selecting the combination of abatement techniques which reduces the existing noise to user specified levels for minimum cost. This methodology, developed in a pilot study of the Massachusetts Bay Transportation Authority (MBTA) rapid transit lines, takes into account the large number of interrelated acoustic and economic considerations present in rail transit systems. The various noise receivers include riders and operating personnel in cars and stations, and individuals in the wayside community. Noise sources include several types of wheel-rail noise, propulsion, power pick-up, auxiliary equipment and braking noise. Noise propagation paths include airborne and structureborne components establishing both direct and reverberant sound fields in tunnels, stations, transit cars, and communities. In the pilot application to the MBTA, minimum-cost noise control options were determined for noise level goals in the range 75 to 90 dBA.

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PREFACE

This report describes a methodology developed by the Transportation Systems Center (TSC) as part of the Urban Rail Supporting Technology Program sponsored by the Rail Programs Branch, Office of Research and Development of the Urban Mass Transportation Administration (UMTA). The TSC noise abatement effort is directed towards reduction of acoustic noise in urban rail systems, thereby contributing to improved environmental quality for users and for the community. This noise program will make available, in a form usable in present and planned urban rail systems, the technology for control of acoustic noise, and it 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 of the technology available for reducing this climate to acceptable levels. Specifically, the assessment of the noise climate and of the state-of-the-art of abatement technology will provide:

- Estimates of capital and maintenance costs for applying proposed noise control standards to operating properties.
- Site specific noise abatement requirements for existing U.S. urban rail transit properties.
- Identification of requirements for new and improved technology.

A pilot study of the Massachusetts Bay Transportation Authority (MBTA) rail rapid transit system was conducted to establish and demonstrate the assessment methodology. The resulting methodology and case studies of the MBTA Blue, Orange, and Red Lines are the subjects of this report.

The methodology as developed in this pilot study is directly applicable to any rail rapid transit system and, conceptually, to other fixed guideway transportation systems. Because of the limited nature of the data sources, certain cautions are noted in the text to indicate the utility of the methodology as well as its limitations. The methodology should be viewed as a first-order methodology which is still under development. The work presented here does not constitute a completed procedure suitable for defining a final optimum noise control program for immediate application to existing rail systems. Further study and development is needed and encouraged. Additional work is already underway to extend the range of applicability of the methodology.

The assistance of the TSC Noise Abatement Group, including E.J. Rickley, R.W. Quinn and N. Sussan, is gratefully acknowledged; they provided the necessary expertise for the recording and reduction of the MBTA noise data. Dr. H. Weinstock and Dr. A. Malliaris offered numerous suggestions which substantially contributed to the formulation of the methodology. In addition, Dr. Malliaris contributed several sections to the original Preliminary Memorandum (Report No. DOT-TSC-UMTA-73-6) upon which this Final Report is based. Finally, the authors wish to thank the MBTA and in particular Mr. John Williams, Chief Development Planner, for their cooperation in this study.

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1. INTRODUCTION

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, it becomes necessary to be able to determine objectively the noise output of an urban rail transit system and to provide a means for abating the noise to desireable or specified levels at minimum cost. The present work was undertaken to develop and test a methodology which would accomplish the above objectives. The methodology which was developed seeks to answer the questions:

a. How can the noise output of a rail transit system be characterized?

b. What is the least costly way to reduce a system's noise output to a specified level?

The method was developed and applied in a pilot study on three rail rapid transit lines of the Massachusetts Bay Transportation Authority (MBTA) System in Boston, Massachusetts. It is, however, general enough to be applied to any rail rapid transit line or system.

The elements of the methodology are illustrated schematically in Figure 1.1. Items A and B are discussed in Section 2 of this Report which presents a methodology for characterizing the noise of urban rail rapid transit systems. The application of this methodology to the three rapid transit lines of the MBTA is then discussed. Section 2 includes descriptions of the general system layout, operational data, and existing noise levels for all relevant receivers, i.e., in-car riders, people in stations, and the wayside communities. A discussion of how acoustically similar segments on each rapid transit line are combined into noise control groups is also included.

Generally speaking, the following ranges of average maximum noise levels exist:

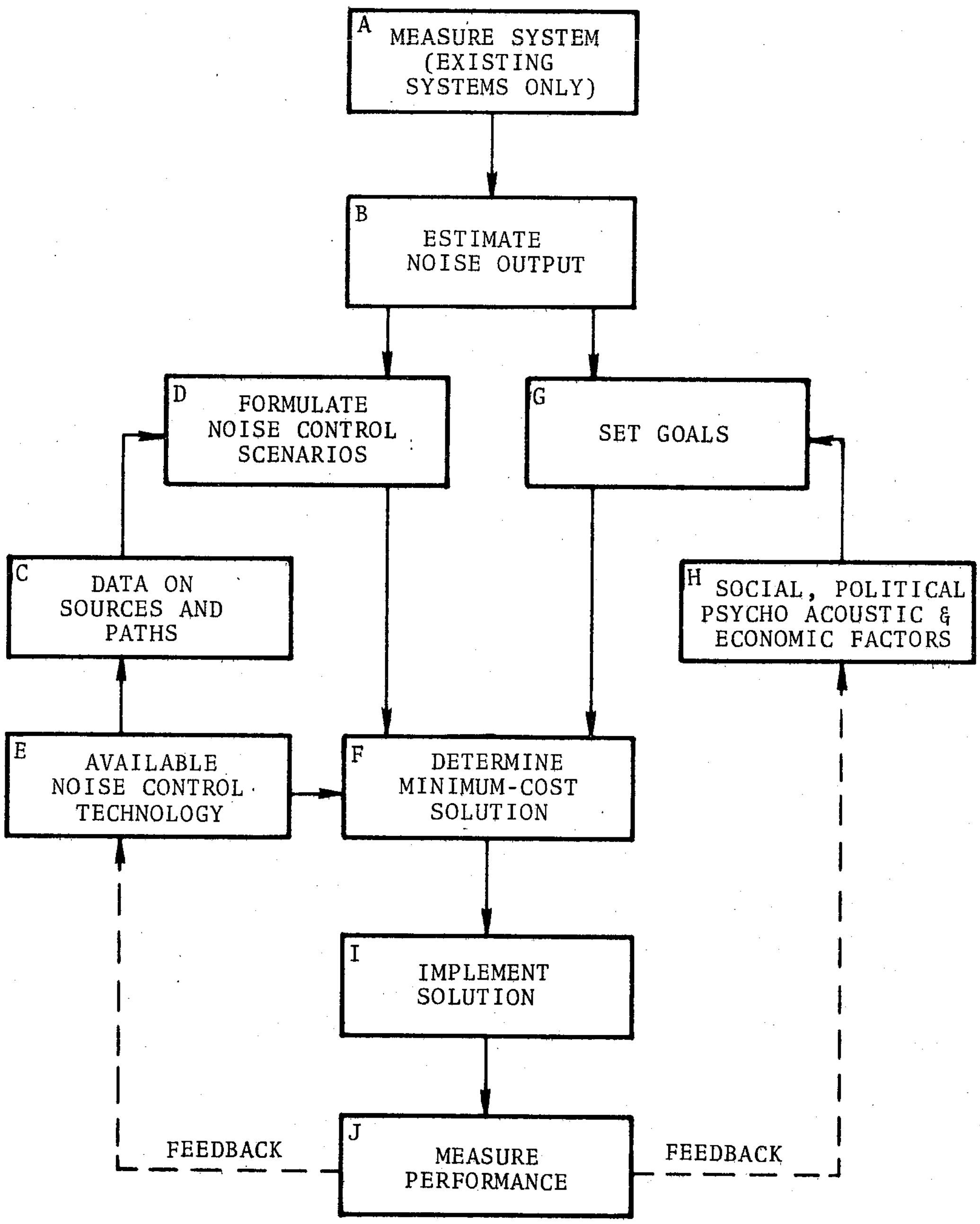


Figure 1-1 Rapid Rail Transit Noise Control Schematic

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

The ranges found in the MBTA generally correspond to typical noise ranges for U.S. rapid transit systems.(1)* Wheel squeal may increase the limits of the stated ranges by as much as 10 dBA. The upper range of these noise levels is sufficient to cause patron and community annoyance including speech interference in cars and stations and task interference in the wayside community.

Items C-F of Figure 1.1 are discussed in Section 3. Starting with the noise control groups from Section 2, the methodology proceeds to:

- Formulate noise control scenarios for each noise group. These scenarios quantify the contribution made by each noise source via each major noise path to the overall noise level at a specified receiver location.
- Compile data on rail rapid transit noise reduction techniques and components, their approximate costs and their effect on noise sources and paths.
- Apply an algorithm (Appendix B) 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.

Item G of Figure 1.1 is addressed only indirectly; the method treats goals as a given input. Parametric goals were used for the study. The remaining items in the schematic were outside the study scope.

*Superscripts refer to references in Appendix D.

2. RAPID TRANSIT NOISE ASSESSMENT

2.1 INTRODUCTION

Any methodology for determining minimum cost noise control requires a quantification of the noise environment in such a way as to allow the engineer to determine the degree of abatement required and the effects of applying noise abatement techniques to the system. The methodology for performing the latter task is described in Section 3.

The amount of noise abatement, required or desired, can be determined only if the system noise environment is measured in a way which permits comparison of the noise with existing noise standards or criteria. The simplest measurable quantity which is compatible with the majority of pertinent noise criteria is the A-weighted sound pressure level (dBA); also called "sound level" or "noise level" in this Report. The methodology developed in this Report requires the following data:

- Continuous sound levels within one or more trains over a complete round trip of each line of the system.
- Continuous sound levels in a selected group of stations during the arrival and departure of several trains.
- Continuous sound levels at a selected group of wayside locations in a variety of neighborhoods during the pass-by of several trans.
- Location identification and characterization of singular noise effects, e.g., location of squeal on curves and impact noise on trackwork.
- The number of cars of each distinct type, classified by acoustic characteristics.
- Configuration and condition of track along the entire system.

The methodology for obtaining this data is described in Section 2.2. Section 2.3 contains a physical description of the MBTA system followed by a summary of the actual MBTA noise measurement data.

2.2 MEASUREMENT METHODOLOGY

Three distinct groups of people must be considered in characterizing the noise on an urban rail transit system. These are:

- Riders and operating personnel in cars
- Patrons and employees in stations
- Individuals in the wayside community

These three categories of noise receivers are considered separately in Sections 2.2.1 through 2.2.3 respectively. Section 2.2.4 discusses the instrumentation used for the MBTA assessment.

The measurement methodology applied to the MBTA Rapid Transit System is not intended for immediate adoption as a measurement standard. It is to be viewed as a first cut at developing a standard methodology for measuring noise in a rapid transit system. Suggestions for improving the methodology are contained in Section 4.2.

2.2.1 In-Car Noise

A sample time history of the noise level in a car traveling between two stations is depicted in Figure 2.1.

In the station, the rider hears noises due to doors opening, people talking, people entering and leaving, air conditioning, car auxiliary equipment (motors, generators, compressors), doors closing, and the air release from the brakes prior to departure. As the train picks up speed, the noise level in the car increases, mainly due to wheel/rail generated noise and propulsion noise. The noise level reaches a plateau value which is constant, on the average, while the train is traveling at constant speed.

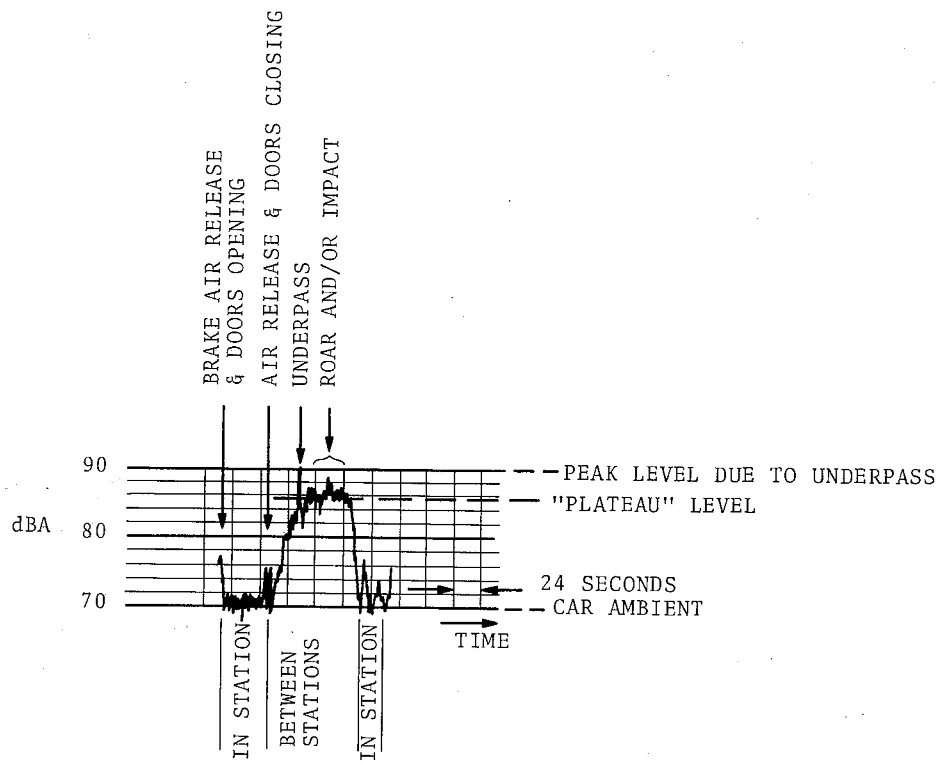


Figure 2-1 Sample Time History of In-Car Noise Levels (dBA)

As the train slows for the next station, the noise level decreases and approaches the car ambient. Since the plateau noise level generally occurs at the maximum speed the train reaches and maintains between stations, the distance traveled by the rider while exposed to this noise represents a significant percentage of the distance between stations. Furthermore, the plateau noise level represents the highest sustained sound level to which the rider is exposed. This quantity has therefore been chosen as a measure of the in-car noise environment.

A number of factors affect the plateau noise level. These include track type (jointed or welded, ballasted or direct fixation); track condition (geometry, loose joints, contaminated ballast); structural configuration (tunnel, at-grade, elevated); vehicle type (acoustically treated, air conditioned, suspension isolation); vehicle condition (door seals, wheel flats); and vehicle speed. It is therefore important to identify these factors as part of the noise assessment of a rapid transit system. Conversely, the plateau noise level in conjunction with some of the system characteristics can be used as an indicator of track and vehicle condition.

In addition to characterizing the in-car noise in terms of the plateau levels between stations, a number of track and vehicle singularities must be considered since they cause sudden deviations from the plateau level or result in annoying noises at lower speeds due to their impulsive or tonal qualities. These singularities include squeal-generating curves, switches and crossovers causing impact noise, underpasses and tunnel entrances and exits causing sudden changes in noise level, squeaking brakes, air release from brake compressors, and banging doors.

Considering the foregoing, the methodology chosen to measure and describe the in-car noise on the MBTA rapid transit system was as follows:

a. Existing data was gathered on system characteristics. This included detailed route maps; location and extent of track types (tie-in-ballast, direct fixation, jointed rail, continuous welded rail); location and extent of tunnel, at-grade, and elevated sections; and number and types of vehicles on each line.

b. System operational data was gathered, including normal operating speeds, train schedules, and information on restricted speed zones.

c. A continuous recording was made of the in-car sound pressure level during a complete round trip. (Ideally this should be performed on at least one of each type of car operating on a given line and cars with noticeable wheel flats or atypical rattles should be avoided.) Location of sensing devices is important. In the MBTA study, the microphones were oriented vertically and placed on a tripod 4' (1.2m) above the floor (roughly at the location of the head of a seated passenger), one third of a car length from either end. This position was selected to avoid being next to a door or over a truck. In addition, the seated position was selected because the noise level in the car is generally higher with fewer people present, i.e., most people would be seated.

d. During each run, continuous voice channel recordings were made to identify noise singularities (such as brake or wheel squeal); landmarks (such as station names or tunnel entrances and exits); track elevation (subway, at-grade, or elevated); subjective reactions to noise and ride roughness; and the presence of particular noise sources such as joint impact and car structure rattling. In addition, the approximate number of people in the car was noted.

e. The variation in sound level within the car and the difference in sound levels in adjacent cars was investigated. This was done by two people, at two different locations in the car. Sound level meters set on slow A-weighted response were used and the data taken at agreed upon intervals, using synchronized watches. Recording of data was by voice on cassette tapes. (This same procedure can be used to evaluate the difference in sound level between that at the standard measurement location described in step (c) above and that in the motorman's cab.)

f. A chart display was made of the noise level (dBA) time histories for each continuous round-trip recording. Stations, tunnel entrances and exits, underpasses, squeal locations and similar significant points were identified on the chart displays using the noise channel data and known system characteristics.

g. The recorded data was divided into a series of plateau values for the rides between stations using the noise level time histories determined in (f). In cases where the ride between stations included more than one type of line construction, e.g., tunnel and at-grade or jointed and continuously welded rail, a plateau level for each segment was determined. In summarizing the data for each line, the arithmetic average of the two plateau levels (one from each direction of the round trip data) was used to represent the in-car noise level over that track segment.

h. The lengths of acoustically similar track segments were combined into noise control groups for each line of the system. Track segments having in-car plateau noise levels falling within the same 5 dBA noise range (centered at 95, 90, 85, 80, 75, and 70 dBA for the MBTA study), and whose track configurations were similar, were considered acoustically similar. For example, all tie-on-ballast, jointed, tangent track sections in tunnels, whose in-car plateau noise levels fell within the range 88-92 dBA were considered acoustically similar and part of the same noise control group. The same track configuration fell into another noise control group if its plateau levels were in the range 83-87 dBA. Furthermore, if another track section had continuously welded rail, as opposed to jointed, but was the same in all other aspects, it was considered to be in another noise control group. As discussed further in Section 3.2.1 and 3.2.2, this type of grouping was chosen because it combines major noise sources and paths which contribute to the plateau levels in a similar way.

i. The characteristics and length of track in each noise control group on each line was summarized.

j. The noise singularities such as wheel squeal locations, underpasses and excessive hunting locations, were located and quantified using the data on the annotated noise level time history displays, (see Section 2.2.1, step (f)) and displayed on a route map of the system.

2.2.2 Station Noise

A sample time history of the noise level at a station platform is shown in Figure 2.2. When no train is present, the waiting patrons hear ambient noise due to station machinery, conversation, and, if the station is above ground, from traffic and aircraft. As a train approaches, the noise level due to wheel/rail and propulsion noise increases to a maximum and then decreases as the train comes to a stop. For many cases, the following effects then occur in rapid succession: (a) door slam, (b) brake air release hiss, (c) 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 a gradual increase in the noise level to another maximum as the train starts up and leaves the station.

The one feature common to all station noise signatures is the presence of the entering and departing maxima. These are generally the highest noise levels experienced by the patrons in the stations. Because of this, the arithmetic average of the maximum entering and departing A-weighted sound pressure levels has been chosen as a simple measure of the station platform noise. This is called the average maximum station noise level in this Report.

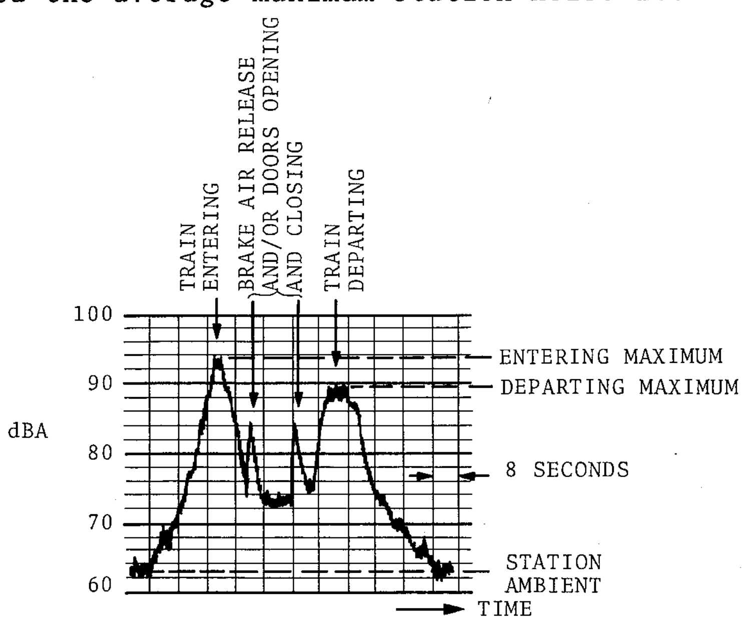


Figure 2-2 Sample Time History of Station Platform Noise Levels (dBA)

Many of the same factors that affect in-car plateau noise levels (see Section 2.2.1) also affect the average maximum station noise level. In addition, station configuration (e.g. plateform between tracks or against a wall) and the station interior absorption characteristics (reverberation time), affect the in-station noise. When possible, these factors should be identified. Since noises such as brake squeal, mechanical door operation, and brake compressor hiss are functions of the vehicle type and condition, the presence of these noises should be noted and quantified for one or two stations but need not be investigated in all stations. Finally the ambient noise level in stations should be determined because the reaction of the patron to the average maximum station noise level may depend on how much above the ambient it is.

The methodology used for measuring and describing station platform noise on the MBTA was as follows:

a. Specific physical station data was gathered including dimensions of the station area, station configuration (e.g. center platform or side platforms), station level (tunnel, at-grade, elevated), and descriptions of any station acoustical treatment (e.g. sound absorbing material on ceiling, barriers between tracks, etc.).

b. Sound pressure levels were recorded on the station platform during several train arrivals and departures, (at least three is recommended). The tape ran long enough to also record the station ambient noise level. The microphone was set on a tripod with its axis vertical, roughly 5'6" (1.6m) above the platform (head height) and six feet (1.8m) from the platform edge, in the center of the station.

c. Concurrent with these recordings, information was taken on the number of people in the station, the presence of any noise singularities (such as wheel flats, wheel squeal, etc), and any other data relevant to the station platform noise level.

d. Where it was impractical to take recordings in a station, hand-held meters were used to determine the maximum entering and leaving A-weighted sound levels and the station ambient noise level. For the MBTA study, this was done with the meter response set for "slow".

e. The variation in sound level on the station platform was investigated. This was accomplished by two (or more) people at different locations on the platform recording the maximum entering and leaving sound levels.

f. Time histories were made of the sound level (dBA) from the recorded data (step (b)). These time histories were used to determine the average maximum sound level and the ambient noise level in the station. These levels were also determined for the stations at which hand-held meters were used (step (d)). For stations at which noise data were not taken, the average maximum station noise level was estimated from measurements at similarly constructed stations on the same line.

g. The lengths of acoustically similar stations were combined, for each line of the system, into noise control groups. Acoustically similar station groups have average peak noise levels in the same 5 dBA range centered at 95, 90, 85, or 80 dBA and have similar station configuration and track construction. (See step (h) of the in-car measurement methodology for a discussion of acoustically similar groups.)

h. The characteristics and combined lengths of stations in each noise control group were summarized.

2.2.3 Community Noise

In the absence of rapid transit trains a wayside observer is exposed to an ambient noise level due to such things as motor vehicles, aircraft, children playing, wind, and industrial noise. As a train approaches, passes and recedes from the observer, the

A-weighted sound pressure level rises to a maximum, then falls back to ambient. Figure 2.3 shows a sample time history of A-weighted sound pressure level at a measurement site during the pass-by of two 4-car trains.

The arithmetic average of the maximum A-weighted sound pressure levels for several pass-bys (referred to as the 'average maximum pass-by noise level' in this Report) has been used as the measure of wayside community noise due to rapid transit operation. The average maximum pass-by noise level 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. It is therefore necessary to identify the type of track (jointed or welded, etc.), the track structural support (at-grade or elevated), the distance to the community along the at-grade and elevated sections of the system, and the vehicle type, condition and speed.

It is also important to determine the ambient noise level as in the case of station noise. The degree to which the average maximum pass-by noise level exceeds the ambient level at a given location may influence the community reaction to the rapid transit noise.

In addition to characterizing the wayside noise in terms of the average maximum pass-by levels, noise singularities such as wheel squeal or impact at switches and crossovers should be located and quantified.

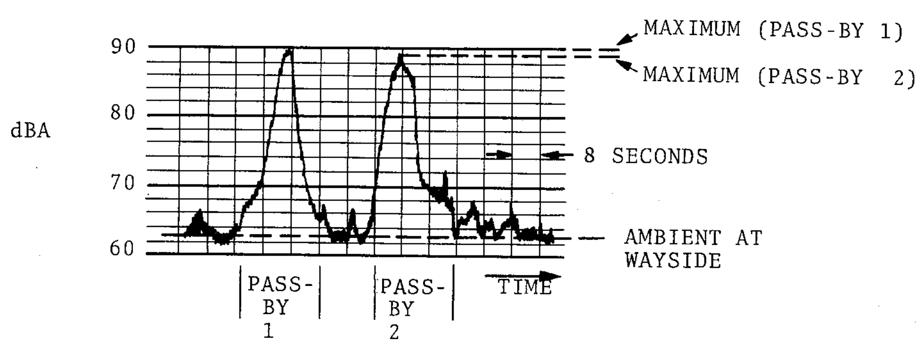


Figure 2-3. Sample Time History of Wayside Noise Levels (dBA) for Two 4-Car Train Pass-Bys in Succession

The following methodology was used for measuring and defining wayside community noise in the MBTA rapid transit system.

a. Route maps were collected, showing location of rapid transit lines relative to buildings in the wayside community, to supplement the system physical data included in step (a) of the in-car noise measurement methodology.

b. Round trips were taken on each line in order to gain familiarity with the system and to supplement the data in step (a). At regular intervals (or landmarks) the distance from the track to the nearest building structure along the wayside was estimated and the type of community (residential, commercial, or industrial) noted. Sites were noted which would permit measurement of wayside noise in a relatively flat, open area, away from building structures or other sound reflecting surfaces. At least one such site was chosen for each type of track construction on a given line.

c. Residential sites where rapid transit noise had created some annoyance were located. In addition to sites identified by complaint data, sites for which the noise consisted primarily of wheel squeal or impact (switches and crossovers) were located and their noise quantified.

d. Train pass-bys (at least three) were recorded at each selected site. The number and type of cars in each train, the location and surroundings of the measurement site, the type of ambient noise at that location, and meteorological conditions were recorded by voice channel or by written note. Where possible, photographs were taken showing the position of the microphone relative to track and to any nearby structure. The recording microphone was equipped with a wind screen and set vertically on a tripod about five feet (1.5m) above the ground and 50 or 100 feet (15 or 30 meters), whichever was more convenient, from the track. For some locations chosen on the basis of complaint data it was necessary to make measurements near buildings. These were made in a nearby open space at approximately the same distance from the track or, in some cases, by placing the microphone out of an open window from the building in question. In all cases, the distance from the microphone to the track was determined.

e. A hand-held meter was used to determine the ambient noise level and pass-by levels where it was impractical to make continuous recordings at a selected measurement site. The measurements were made for at least three train pass-bys. The meter was set on "slow", A-weighted response.

f. Time histories were made of the sound level (dBA) from the recorded data (step (d)). These were used to determine the average maximum pass-by level and the ambient sound level at each measurement site.. These levels were also determined for the sites at which hand-held meters were used (step (e)). Where wheel squeal or impact at special trackwork was the predominant noise source, the average peak level as well as the ambient noise level were determined for the recorded pass-bys.

g. The typical distance from the track to the nearest building in the residential, commercial and industrial communities along the at-grade and elevated sections of each line was plotted on a schematic of the rapid transit system route. The distance of each measurement site from the track and the associated maximum pass-by and ambient noise levels were also indicated.

h. The track was divided into several sections according to the typical distance to the nearest residences for each between-station length of the right-of-way adjacent to residential communities. For the MBTA study, the following distance ranges were used to group track segments: 75', 75'-150', 150'-300', 300'. Each of these track sections was further divided into segments having similar track construction and elevation (at-grade or elevated).

All the track segments on a line falling into the same distance range and having the same track configuration were combined into noise control groups. The significance of these noise control groups is briefly discussed in step (h) of the in-car measurement methodology and in more detail in Sections 3.2.1 and 3.2.2.

i. The wayside levels for track segments comprising each noise control group were estimated using the average measured maximum pass-by levels as a basis and accounting for geometric spreading of the acoustic energy from the train to 50', 100', 200' and 400' for the ranges 75', 75'-150', 150'-300', 300' respectively. The spreading was calculated for the MBTA study by modeling the train as an incoherent line source on a perfectly reflecting plane. The corrections based on this model are shown in Figure 2.4. The levels were normalized to those for a four car (300') train.

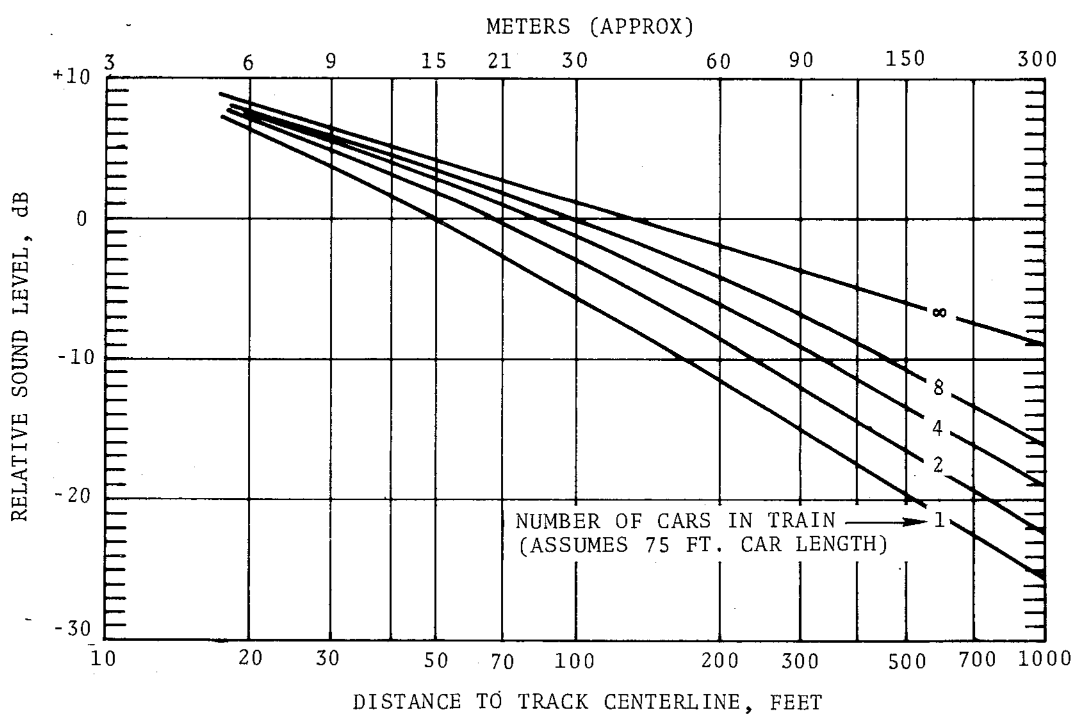


Figure 2-4. Change in Sound Level with Distance from the Track Relative to a One Car Train at 50 Feet

j. The track characteristics, range of distances from the track to the community, estimated pass-by noise level, and total length of track were summarized for each noise control group.

2.2.4 Instrumentation

The instrumentation used for the field measurements included B&K Type 4134 1/2-inch microphones with B&K UA-0237 windscreens, GR 1565B hand-held sound level meters, a Nagra IV-S tape recorder, and Sony portable cassette recorders for voice data. Laboratory data reduction employed a GR Model 1521 Graphic Level Recorder and a GR Model 1925 Multifilter for obtaining A-weighted output.

2.3 MBTA NOISE ASSESSMENT

The data summarized in this Section were obtained by applying the methodology described in Section 2.2 to the three rapid transit lines of the MBTA rail transit system.

Section 2.3.1 includes a description of the physical characteristics of the MBTA system. The noise measurement data is presented in Section 2.3.2 and is discussed in Section 2.3.3.

2.3.1 System Description

The Massachusetts Bay Transportation Authority rail transit system comprises a light rail trolley line identified as the Green Line and three rapid transit lines, color coded as the Blue Line, the Orange Line and the Red Line. The Green Line was not included in this Study. The route structure is shown in Figure 2.5.

The Blue Line is six miles long and has twelve stations. Running time is eighteen minutes. 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. 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 air-conditioned or acoustically treated.

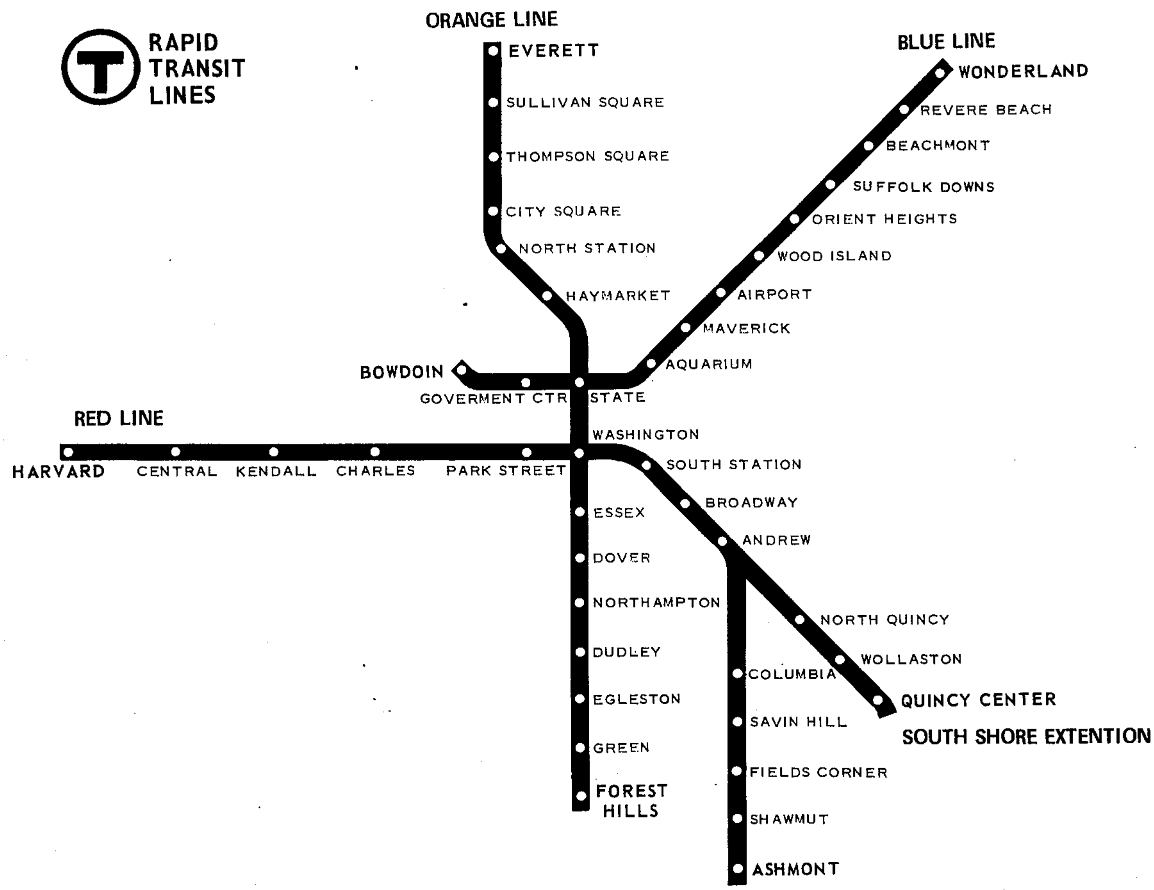


Figure 2-5. MBTA Rapid Transit Lines - Schematic

The Orange Line has 8.5 miles of double track and fifteen stations. The running time is about 30 minutes. Starting from Everett, the line runs on an elevated structure for 3.8 miles to North Station, the fifth station on the line. From there it enters a 1.2 mile tunnel with four underground stations, the last being 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. They average about 15 years old and have no special acoustic treatment. They are not air-conditioned.

The Red Line comprises two branches. The original line, referred to as the Ashmont Branch, is 9.0 miles long with a 25 minute running time covering 14 stations including the terminals, Harvard and Ashmont. Beginning at Harvard the Line runs underground for two additional stations (2.3 miles) to Kendall. It then emerges and runs across the Charles River to Charles Street Station (.4 miles). Charles Street Station and the adjacent track (.1 mile) is elevated. The next five stations (2.8 miles) to Andrew are underground. Emerging to grade level after Andrew this line continues through five stations (3.4 miles) to Ashmont. The Ashmont line has about 1-1/2 miles of interface with residential neighborhoods.

The new South Shore Extension of the Red Line covers 6-1/4 miles (4 stations) of grade level track, starting at Andrew and ending at Quincy Center, with 3 miles adjacent to residential communities. The running time from Harvard to Quincy Center is about 25 minutes. The Line has a total of 168 cars. Of these, 92 are older cars built in 1963 and called "Bluebirds" because of their blue painted exteriors. They are not air-conditioned or acoustically treated. These cars 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, have a high-car-body acoustic transmission loss, and are capable of 80 mile per hour operation. Silverbirds ordinarily operate only between Harvard and Quincy Center.

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

2.3.2 In-Car Noise Data

Continuous recordings of the in-car sound pressure levels were made for complete round trips on each line, including two on the Red Line; one each on a Bluebird and a Siverbird (Section 2.2.1, steps 3 and 4). The in-car data for the Silverbirds were taken from a previous study by the Transportation Systems Center.[23] The time history of the in-car noise levels (dBA) for each round trip (Section 2.2.1, step (6)) are displayed in Appendix A, Figures A-1 thru A-3.

The recorded data for each line have been divided into a series of plateau values for the rides between stations (Section 2.2.1, step (g)). 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 for the Orange Line are shown in Figure 2.6 where each plateau level is the arithmetic average of the two levels (one from each direction of the round trip) obtained for each track segment. Similar results for all three lines are contained in Appendix A, Figures A-4 thru A-6.

In Table 2-1, lengths of acoustically similar track have been combined into noise control groups (Section 2.2.1, steps (h) and (i)). The table lists the track segments within each group and gives their total double track length and plateau noise level range. Table 2-2 gives the vehicle and track characteristics for each in-car noise control group.

TABLE 2-1. LINE SUMMARIES FOR IN-CAR NOISE

BLUE LINE

TRACK TYPE	97 - 93 dBA			92 - 88 dBA			87 - 83 dBA		
	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP
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 10c, 11b	R5

ORANGE LINE [(a)]

TRACK TYPE	92 - 88 dBA			87 - 83 dBA			82 - 78 dBA		
	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP
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	R8

RED LINE (ASHMONT)[(b)]

TRACK TYPE	92 - 88 dBA			87 - 83 dBA			82 - 78 dBA		
	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP
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	R8

RED LINE (SOUTH SHORE EXTENSION)

TRACK TYPE	82 - 78 dBA			77 - 73 dBA			72 - 68 dBA		
	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP	LENGTH (ft)	TRACK SEGMENTS	NOISE GROUP
TUNNEL	-	-	-	1,760	9a	R11	-	-	
AT-GRADE	-	-	-	-	-	-	28,540	14a,14b, 14d,14e, 14f, 14h 15a,15b	R10

(a) In addition to the track segments given in the chart, elevated sections 4, 5a and 12a account for 4530 ft at 75 dBA

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

NOTE: Refer to Appendix A for locations of all track segments.

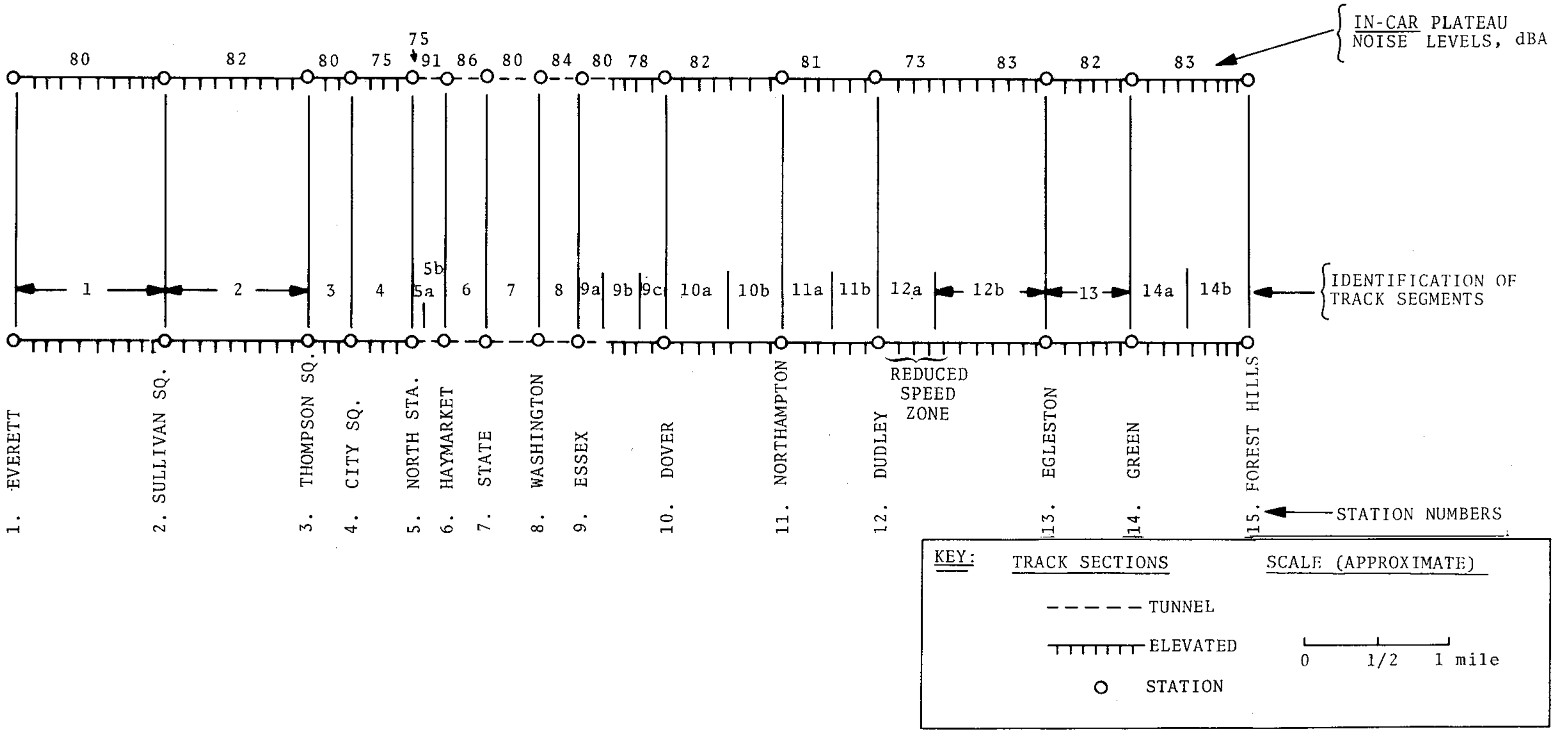


Figure 2-6. In-Car Plateau Noise Levels for the MBTA Orange Line

TABLE 2-2. DESCRIPTION OF IN-CAR NOISE CONTROL GROUPS (1 of 2)

Noise Control Group	Plateau Noise Level (dBA)	Track Description			Car Description			Estimated* Vehicle Speed (mph)
		Elevation	Rail Surface	Rail Support	Wheel Tread	Acoustic Leaks	Other	
R1	95	Tunnel	Jointed or occasionally field welded; fairly rough	Wood tie on 6" - 8" of ballast	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	40 - 45
R2	90	Tunnel	Jointed or occasionally field welded; farily rough	Wood tie on 6" - 8" of ballast	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	30 - 40
R3	85	Tunnel	Jointed or occasionally field welded; fairly rough	Wood tie on 6" - 8" of ballast	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	20 - 30
R4	80	Tunnel	Jointed or occasionally field welded; fairly rough	Wood tie on 6" - 8" of ballast	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	15 - 20
R5	85	At-grade	Jointed or occasionally field welded; fairly rough	Wood tie on 12" of ballast	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	35 - 45

*Vehicle speed was not estimated during the data collection. Values here are estimated based on the overall noise level and track type.

TABLE 2-2. DESCRIPTION OF IN-CAR NOISE CONTROL GROUPS (2 of 2)

Noise Control Group	Plateau Noise Level (dBA)	Track Description			Car Description			Estimated* Vehicle Speed (mph)
		Elevation	Rail Surface	Rail Support	Wheel Tread	Acoustic Leaks	Other	
R6	80	At-grade	Jointed or occasionally field welded; fairly rough	Wood tie on 12" of ballast	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	25 - 35
R7	85	Elevated	Jointed; fairly rough	Wood ties bolted to open deck steel structure	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	30 - 40
R8	80	Elevated	Jointed; fairly rough	Wood ties bolted to open deck steel structure	Rough surface but no large flats	Untreated ventilation system; poor door seals	Fairly hard suspension; no interior absorption treatment	20 - 30
R9	80	Tunnel	Jointed or occasionally field welded; fairly rough	Wood tie on 6" - 8" of ballast	Rough with some flats	Air conditioned; good door seals; high car body transmission loss	Soft suspension; interior absorption	30 - 40
R10	70	At-grade	CWR; fairly rough	Concrete ties on 12" of ballast	Rough with some flats	Air conditioned; good door seals; high car body transmission loss	Soft suspension; interior absorption	40 - 50

*Vehicle speed was not estimated during the data collection. Values here are estimates based on the overall noise level and track type.

The information presented in Figure 2.6 and Tables 2-1 and 2-2 does not include noise singularities such as wheel squeal or excessive hunting. These are summarized in Figure 2.7 which indicates the squeal, hunting, and underpass and tunnel entrance locations. In addition, the average of the maximum dBA levels for two passes is given at each of the locations.

Only limited measurements were made to determine the variation of sound level within a car. Based on measurements in two cars, a Red Line Silverbird and a Blue Line car, the variations in sound level were found to be less than 3 dBA.

2.3.3 Station Noise Data

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 hand-held meter readings were obtained. (See steps (b), (c), and (d) of the station measurement methodology, Section 2.2.2). The ambient and average maximum station noise levels were determined for each of the measured stations (Section 2.2.2, Step (f)) and this data for the Orange Line is summarized in Figure 2.8. Similar data for all three lines are contained in Appendix A.

From data on the physical characteristics of the track and stations (Section 2.2.2, step (a)), a number of station track configurations were identified. These are shown in Figure 2.9. For stations at which noise data were not taken, the average maximum noise levels were estimated from measurements at similarly constructed stations on the same line (Section 2.2.2, Step (f)).

In Table 2-3, lengths of acoustically similar stations have been combined into station noise control groups (see Section 2.2.2, steps (g) and (h)). This Table identifies the stations within each group, the track configuration type (from Figure 2.9), the range of noise levels and the total station length in each category.

A number of simultaneous measurements were made at various positions in the Kendall Square Station (Red Line) in order to estimate the dependence of the calculated average of the entering

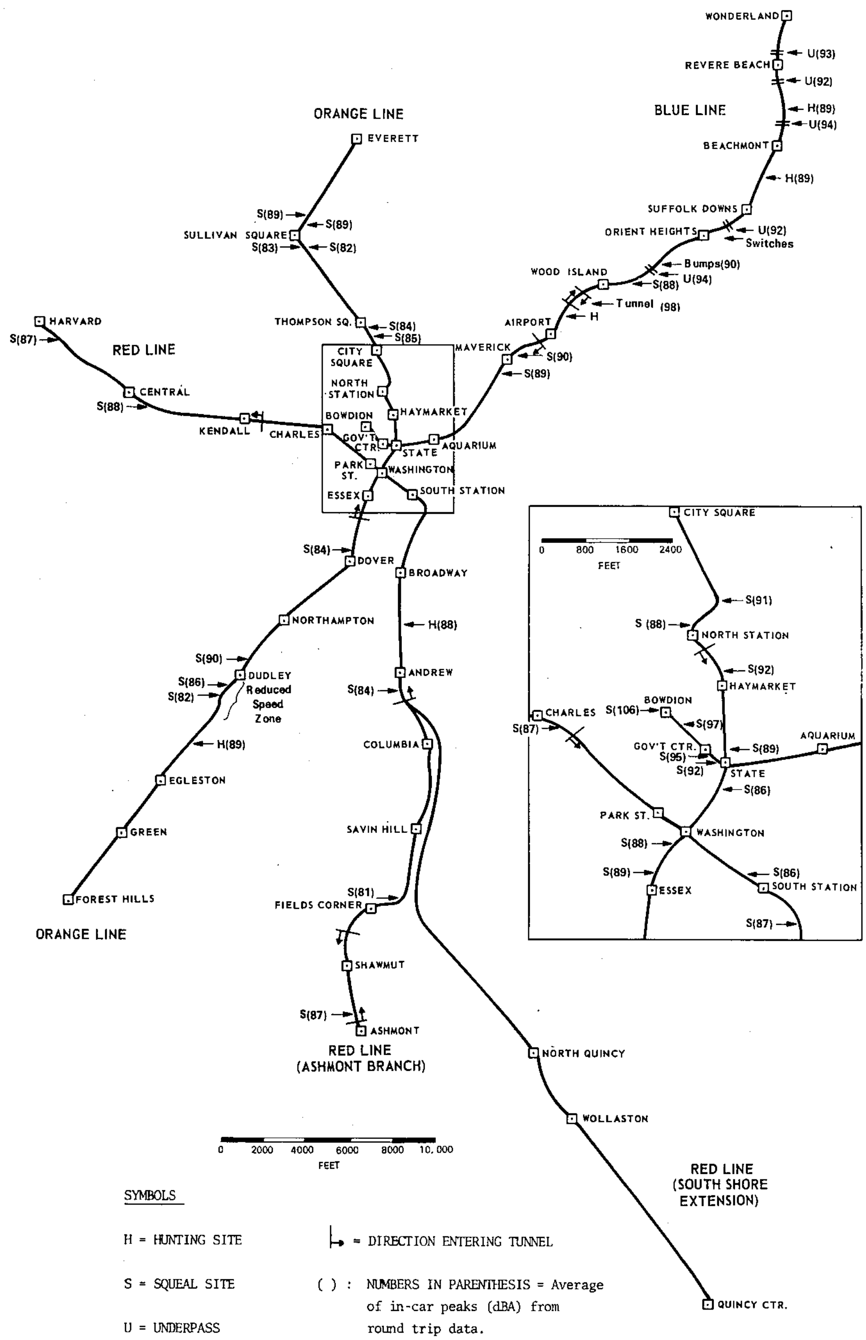


Figure 2-7. Site Specific In-Car Noise Problems

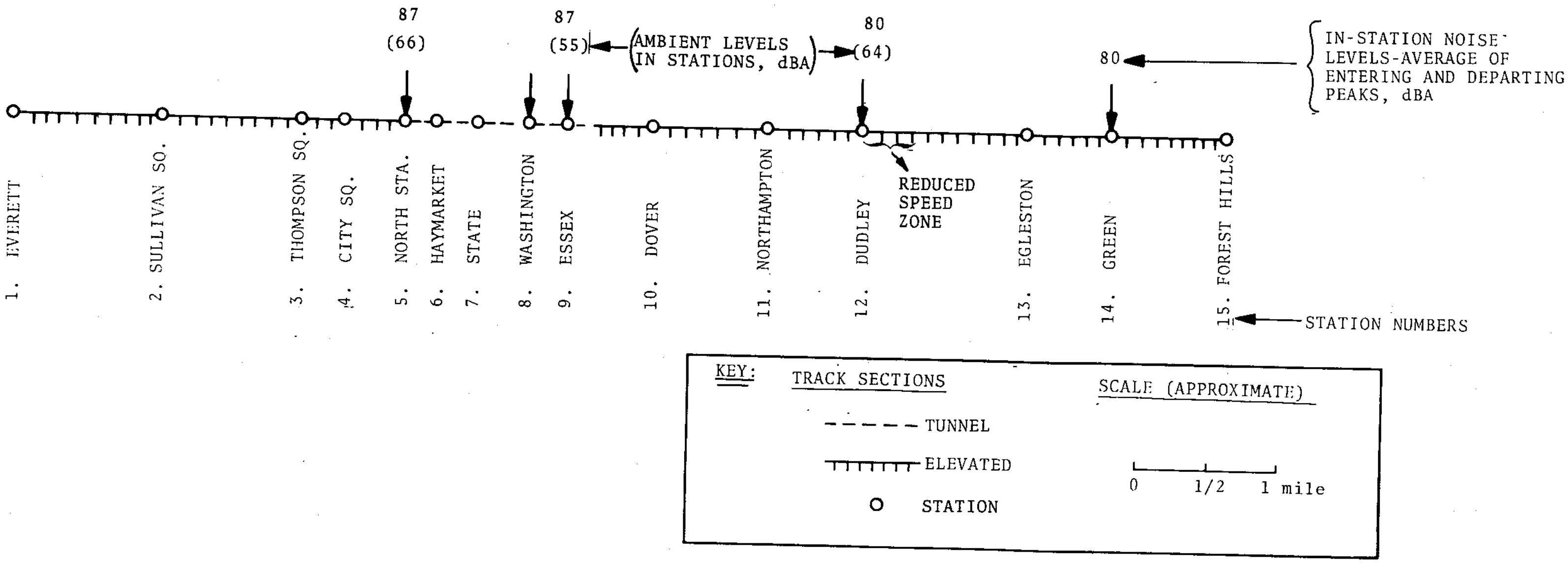


Figure 2-8. Average Maximum Station Platform Noise Levels for the MBTA Orange Line

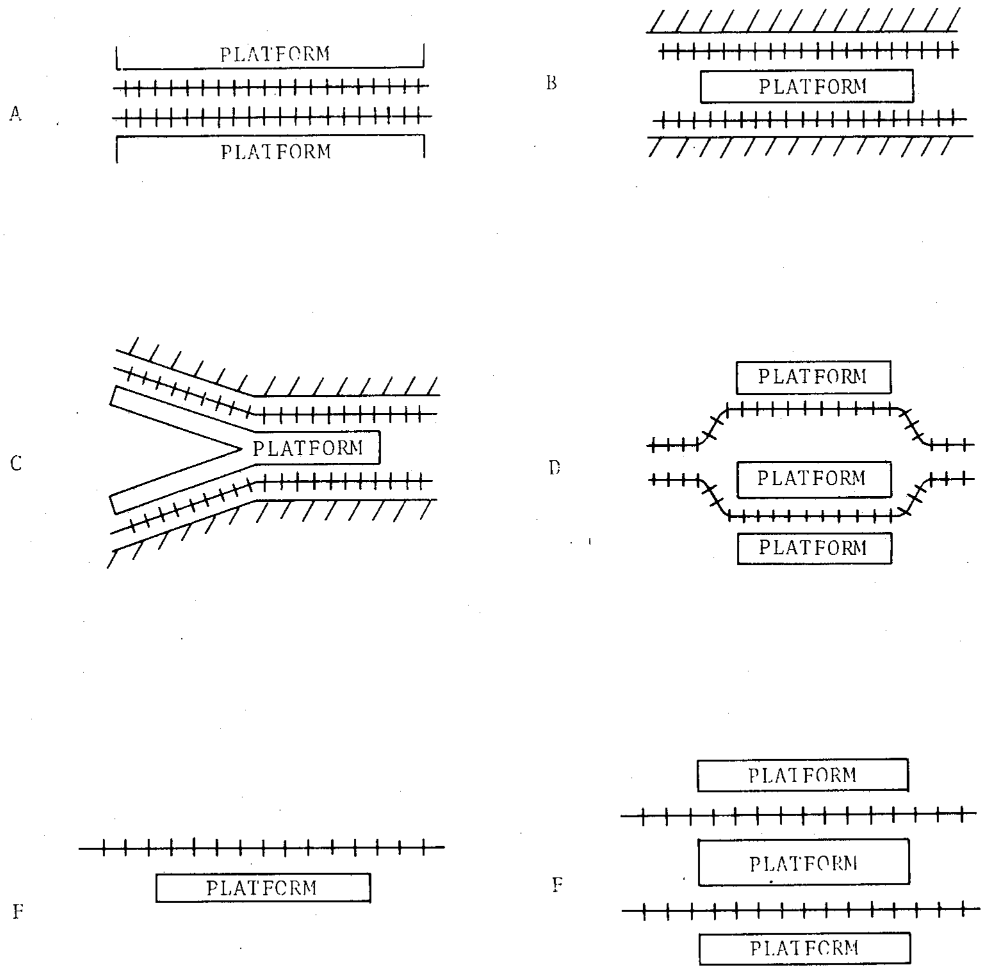


Figure 2-9. Track Configurations at Stations

TABLE 2-3. SUMMARY OF STATION PLATFORM NOISE FOR MBTA BLUE; ORANGE AND RED LINES

Blue Line

TRACK TYPE	97-93 dBA			92-88 dBA				87-83 dBA			
	LENGTH(FT)	STATION#	TYPE	LENGTH(FT)	STATION#	TYPE	NOISE GROUP	LENGTH(FT)	STATION#	TYPE	NOISE GROUP
GRADE				1860	6,7,9,10, 11,12	A	S4	310	8	A	S7
TUNNEL				220	3	A	S2	200	4	B	S6
TUNNEL				960	2,5	B	S3				
TUNNEL				480	1	C	S3				

Orange Line

TRACK TYPE	92-88 dBA	87-83 dBA				82-78 dBA			
		LENGTH(FT)	STATION#	TYPE	NOISE GROUP	LENGTH(FT)	STATION#	TYPE	NOISE GROUP
ELEVATED		350	2	D	S11	480	12	D	S14
ELEVATED		290	5	B	S10	710	3,11	B	S13
ELEVATED		410	4	A	S9	1840	1,10,13, 14,15	A	S12
TUNNEL		2920	6,7,8,9	A	S5				

Red Line

TRACK TYPE	97-93 dBA				92-88 dBA				87-83 dBA			
	LENGTH(FT)	STATION#	TYPE	NOISE GROUP	LENGTH(FT)	STATION#	TYPE	NOISE GROUP	LENGTH(FT)	STATION#	TYPE	NOISE GROUP
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	E	S3				
TUNNEL					360	5	F	S3				
ELEVATED									310	4	A	S9

Notes: Refer to Appendix A for identification of station numbers.
Refer to Figure 2.9 for identification of station configurations.

and departing maxima on measurement position in station. For this station the reverberant sound field dominated the direct field, resulting in less than a 3 dBA variation with position.

2.3.4 Community Noise Data

Eleven sites were selected for community noise measurements. The sites were chosen from informal complaint data obtained from discussions with the MBTA, from study of the proximity of the right-of-way to neighboring residential communities, and from consideration of track type (Section 2.2.3, Steps (a) and (b)).

At each site, the sound pressure level was measured in an open area, at the same distance from the track as typical wayside structures, during several train pass-bys. In some cases the pass-by measurements were made from outside a window of a nearby residence (Section 2.2.3, steps (d) and (e)). This data was then used to determine the ambient and average maximum pass-by levels at each site (Section 2.2.3, step (f)). The type of track, microphone location and average maximum pass-by level for each site is given in Appendix A, Table A-1.

The relationship of these data to the wayside communities along the Orange Line can be seen in Figure 2.10. This figure shows schematically the measured levels and the approximate distance to the nearest wayside structure (Section 2.2.3, step (2)). Isolated structures deviating from the general pattern of a community are not shown. 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 and similarity of track configuration (Section 2.2.3, step (h)). These segments are also labelled on Figure 2-10. Similar results for all three MBTA lines are contained in Appendix A.

Estimated wayside levels were determined for each segment not having an actual measurement by extrapolating from the measurements of an acoustically similar segment. Spreading was calculated

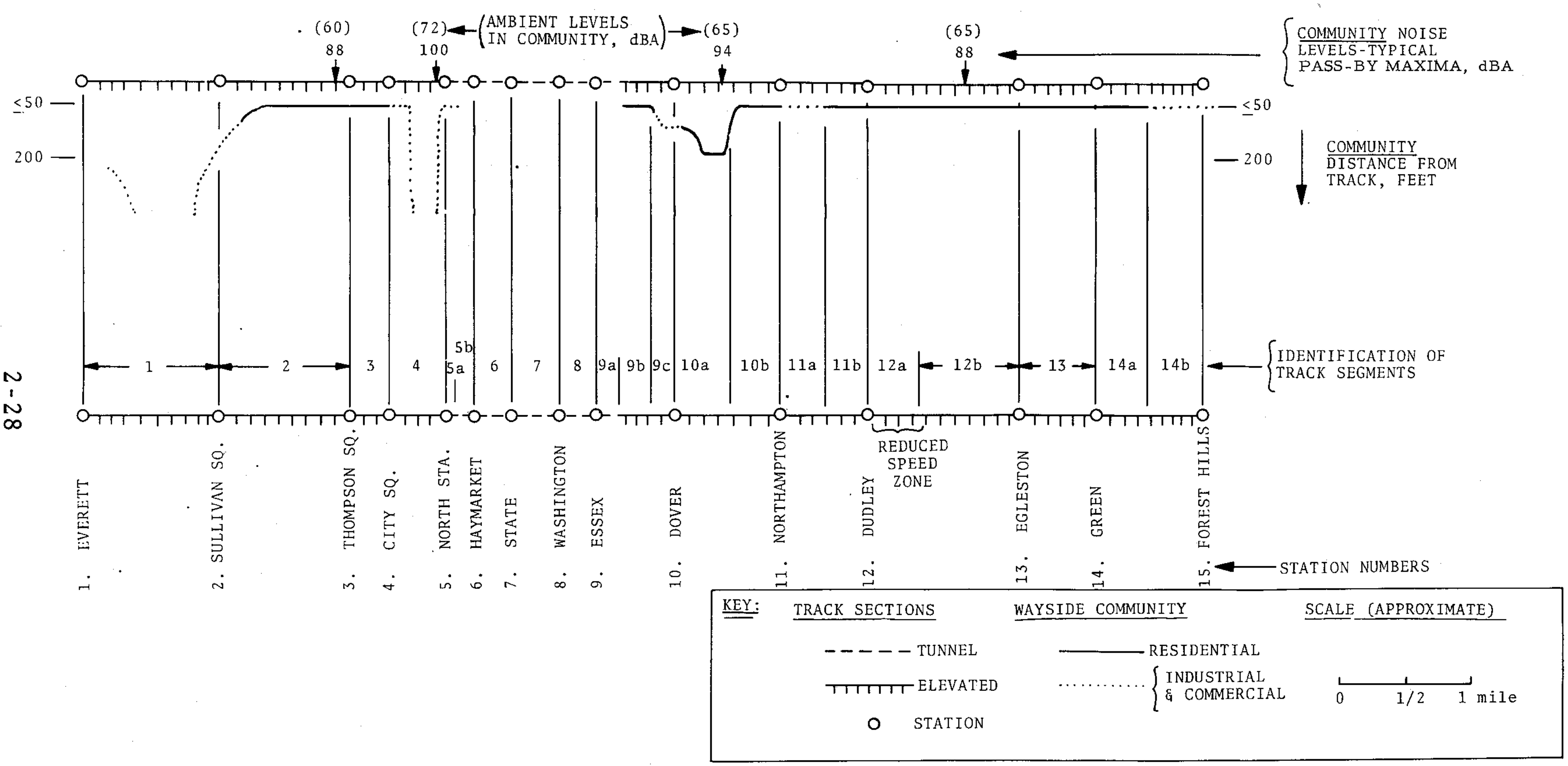


Figure 2-10. Typical Distance to Wayside Community and Average Maximum Pass-by Levels along the MBTA Orange Line

by modeling the train as a 300 foot long incoherent line source (Section 2.2.3, step (i)). Table 2-4 lists the pass-by noise levels thus obtained for segments of the right-of-way adjacent to residences. Acoustically similar segments have been combined into noise control groups and the total double track length in each group is given (Section 2.2.3, step (j)).

2.3.5 MBTA Noise Summary

The MBTA noise status is summarized in Figure 2-11. This Figure indicates the length of track on each line for which the noise levels at the indicated receiver (in-car rider, station patron, residential wayside community) fall into 5 dBA ranges centered at 70, 75, 80, 85, 90, and 95 dBA. A number of observations regarding the information in this figure as well as that in Tables 2-1, -3, and -4 are made below:

In-Car Noise

- The noise levels in the new, acoustically treated Silverbirds on the South Shore Extension are substantially lower than in other cars elsewhere in the system. A direct comparison of the in-car noise levels in the Silverbirds and Blue birds riding over the same track sections show the Silverbirds to be 8 dBA quieter.
- The highest in-car levels exist while the cars are running in tunnel sections. The approximate average plateau levels, excluding the Silverbirds, on tunnel, at-grade, and elevated sections are 87, 83, and 81 dBA respectively. For comparison, typical interior noise levels in other transportation vehicles[1] range from 68 dBA in passenger trains to 83 dBA in commercial aircraft.
- The noise levels in the Blue Line cars are generally higher than in the cars on the other two lines.

TABLE 2-4. LINE SUMMARIES FOR RESIDENTIAL PASS-BY NOISE

MAX. PASS-BY LEVEL		97-93 dBA			92-88 dBA			87-83 dBA			82-78 dBA		
MBTA LINE	TRACK TYPE	LENGTH (FT)	TRACK SEGMENTS	NOISE GROUP	LENGTH (FT)	TRACK SEGMENTS	NOISE GROUP	LENGTH (FT)	TRACK SEGMENTS	NOISE GROUP	LENGTH (FT)	TRACK SEGMENTS	NOISE GROUP
BLUE LINE	AT GRADE				2600	9b,10e	C1	5710	6c,7b,8c, 10c,10d	C2	3650	7c,8b	C3
ORANGE LINE	ELEVATED	1860	10b	C4	18980	2,3,9b, 10a,11b, 13,14a	C5				1000	12a	C6
RED LINE	AT GRADE (JOINTED)				3610	9b,10b	C1	2640	11b	C2	1380	12a	C3
	AT GRADE (WELDED)							13390	14b,e, 15a,16	C7			
	ELEVATED (JOINTED)				510	4a	C5						
	ELEVATED (WELDED)							950	14c	C8			

NOTES: Locations of track segments are given in Appendix A

Track characteristics for each noise group are given in Table 3-9.

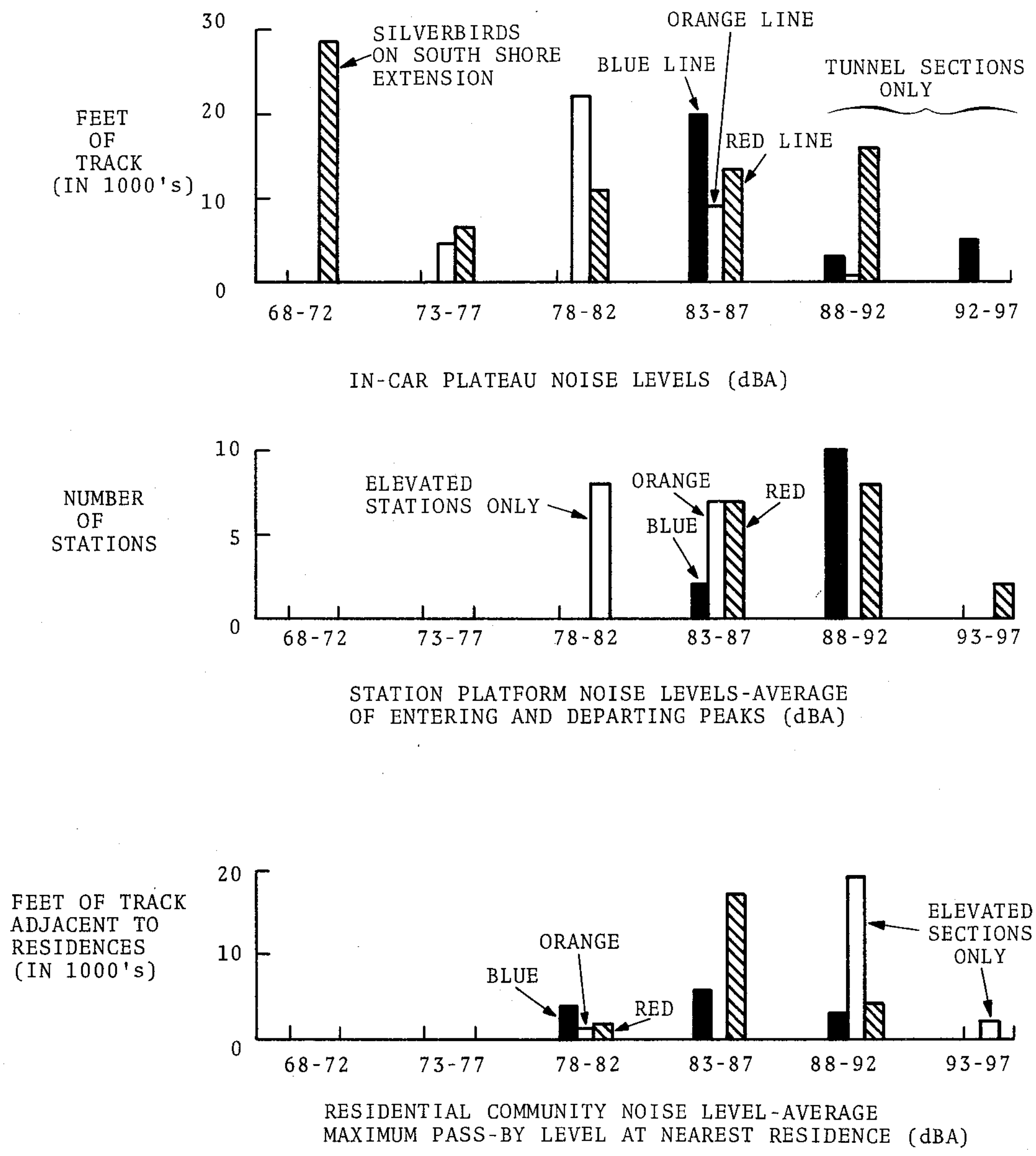


Figure 2-11. Summary of MBTA Noise Status

Station Noise

- The noise levels in the elevated Orange Line stations are significantly lower than in other stations.
- The approximate average maximum station platform noise levels in tunnel, at-grade, and elevated stations are 90, 87, and 82 dBA respectively.
- The exterior noise levels of the Silverbirds are not noticeably lower than for any other cars.

Residential Community Noise

- The wayside levels near elevated track sections are generally higher than for at-grade sections. This could be due to both increased noise radiation from the track support structure and the closer proximity of the residences to the elevated track sections.
- The approximate average maximum pass-by level outside the nearest residences is 87 dBA. Based on a five second pass-by duration (duration of noise level within 10 dBA of the maximum) and 288, 30 and 32 passbys during (0700-1900 hours), evening (1900-2200 hours) and night (2200-0700 hours) respectively, the Community Noise Equivalent Level (CNEL) can be calculated.[1,22] The result for the average maximum pass-by level of 87 dBA is a CNEL of 70 dB. For an urban residential community, relatively near to busy roads and industrial areas, and with considerable previous exposure to the intruding noise, a -10 dB correction is made to the CNEL to obtain a Normalized Community Noise Equivalent Level (NCNEL) of 60 dB.[1] According to Reference (1) an NCNEL of 60 dB corresponds to community reactions varying from no complaint to sporadic complaints. This agrees with MBTA experience.

3. RAPID TRANSIT NOISE CONTROL

3.1 INTRODUCTION

In urban rail transit noise control, there are a large number of interrelated acoustic and economic considerations. People exposed to noise (i.e., receivers) include riders and operating personnel in cars and stations, and individuals in the wayside community. Noise sources include several types of wheel-rail noise, as well as power pickup, propulsion, braking and auxiliary equipment noise. Noise propagation paths include airborne and structure-borne components with both direct transmission into, and reverberant build-up in tunnels, stations, transit cars, and communities. In most cases, several sources contribute to the noise level at any receiver via each of several paths. Accordingly, there are a large number of noise control techniques, each having an associated installation and maintenance cost, to be considered in reducing rapid transit noise at the various receivers.

A methodology has been developed to select the combination of techniques which reduces noise under these circumstances by any specified amount for minimum cost. The elements of this methodology are illustrated schematically in Figure 1.1. Items A and B have been discussed in Section 2 of this report. Items C - F are the major elements of the noise control methodology and serve as an outline for the four parts of Section 3.2. Section 3.3 describes the results of a pilot application of the noise control methodology to the Boston MBTA System.

A word of caution is advisable at this point: *the methodology described here should be viewed as a first-order methodology, still under development. Because the data on cost and effectiveness of noise control treatments is limited and because the measurement techniques for quantifying the predominant noise sources and paths have not yet been refined, the application of this methodology to existing systems should be used only to get an estimate of the minimum cost noise control options.*

3.2 METHODOLOGY FOR MINIMUM-COST NOISE CONTROL

The methodology, which is described in detail in Sections 3.2.1 - 3.2.4, comprises the following steps:

a. (Items A and B, Figure 1.1) Measure or estimate the overall noise level at standard receiver locations along each line of the rapid transit system. This includes grouping together track segments with similar construction and operating characteristics as well as with similar overall noise levels (within 5 dBA) at the receiver locations. These groups of similar track segments are called noise control groups. In addition, locate and measure those noise phenomena denoted as noise singularities, (see Section 2.2.1 step (j)) such as wheel squeal, noise at excessive hunting locations and, in stations, brake squeal, mechanical door operation, and brake air release. The procedure for performing step (a) is described in Section 2.2.

b. (Item C, Figure 1.1) Identify the major sources of noise and predominant noise transmission paths to specified receivers for all noise control groups making up a given line. Each noise control group has been selected in such a way as to have similar noise sources and transmission paths to the specified receiver location. This task is discussed in Section 3.2.1.

c. (Item D, Figure 1.1) For each noise control group, estimate the noise level at the receiver contributed by each major noise source via each major transmission path. Such a quantification of the source-path contribution to the noise level at a receiver is called a noise control scenario. The formulation of scenarios is discussed in Section 3.2.2.

d. (Item E, Figure 1.1) Compile data on available noise control technology. For each abatement technique, determine which noise sources or paths are affected, the potential noise source reduction or path attenuation, the installation and maintenance costs, and any constraints or special considerations associated with its use. A first-order compilation of this type is included in Section 3.2.3.

e. (Item F, Figure 1.1) Using data compiled in step (d) above, compute the costs of eliminating (or substantially reducing) the noise resulting from the noise singularities identified in step (a). Then compute the costs and noise reductions achievable by application of selected combinations of abatement techniques to the scenarios defined in step (c). By an iterative process, determine the set of techniques which achieve the desired goals for a given receiver along the entire line for minimum cost. This procedure is discussed further in Section 3.2.4. A computer algorithm for performing the iterative process is described in Appendix B.

3.2.1 Urban Rail Noise Sources, Paths, and Receivers

As previously noted, it is typical for several noise sources, through various paths, to contribute significantly to the noise level at a given receiver. The reduction of noise from a single source (or path) is therefore likely to have only a minor effect on the overall noise level at that receiver. Therefore, from the point of view of noise control, it is useful to identify the noise sources and paths contributing to the receiver noise level. Table 3-1 is a general compilation of noise sources, paths, and receivers in rail transit systems. Most of the predominant noise sources contained in this table have already been mentioned in Sections 2.2.1, 2.2.2, and 2.2.3, on in-car, station, and community noise, respectively.

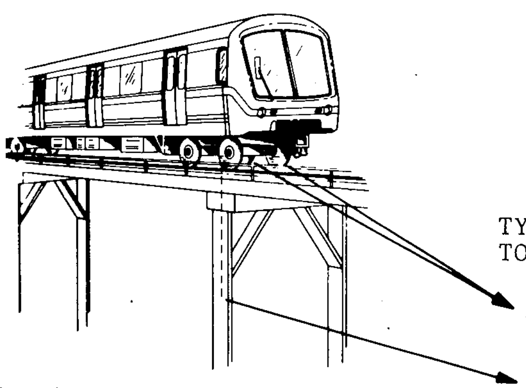
For each receiver category, different combinations of sources and paths may contribute to the overall noise level. As an example, Figure 3.1 illustrates some of the sources and paths that contribute to community noise along an elevated line.

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

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

In most rapid transit systems the dominant noise source is wheel/rail interaction; the next most important source is the propulsion system. The predominant paths are dependent on both the receiver and the noise source. Referring again to the example of community noise near an elevated structure (Figure 3.1), the noise due to wheel/rail interaction is radiated directly from the wheels and rails, and from the elevated structure which is set into vibratory motion by the same wheel/rail interaction. The propulsion system on the other hand, does not significantly excite the guideway and radiates noise to the community directly from the under-car area.

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. In order to simplify the overall system description and noise control problem the system is divided into a number of segments, the fundamental assumption being that sources, paths, and receivers can be approximated by some



NOTE: Wheel-rail noise originates from two causes, joint impacts and microroughness of wheel and rail (so-called roar noise). Noise from these sources propagates to community by two paths: (1) direct airborne, (2) vibration and radiation from elevated structure. Noise from third-rail power pickup, propulsion motors, and auxiliary equipment propagates only by direct path.

Figure 3-1. Contribution of Multiple Sources and Paths to Noise Level in Community average values over each segment. In order for these segments to be properly approximated by a given set of sources, paths, and receiver locations, the track type and condition, vehicle type and condition, vehicle speed, and receiver location must be relatively similar for each segment. These restrictions are just those which were imposed in formulating the noise control groups as part of the measurement methodology. (For details, see Section 2.2.1 - step (h) for in-car, station, and community noise control groups respective-ely.) For each rapid transit line this means that the overall noise control problem is a collection of independently posed segment-problems whose solutions cannot be determined independently because any noise control method applied to the railcars will affect all track segments.

3.2.2 Formulation of Noise Control Scenarios

Section 3 presents a methodology for determining minimum cost solutions to noise control problems in rapid transit systems. Since the ultimate objective is to reduce the noise at a given receiver to an acceptable level, as yet undefined, the effect of a given noise control technique on the noise level at a given receiver must be predictable. This requires knowledge of the contribution to the noise level at the receiver from each noise source-path combination.

To illustrate this, consider evaluating the effect of putting barriers along the top sides of a closed deck elevated structure for the example of Figure 3.1. Assume that the desired type of barrier provides a 12 dBA reduction (insertion loss) in the way-side noise level at 50 feet when used along an at-grade section of track. If this same barrier is installed on the elevated structure, taking care not to leave any air gaps, the noise radiated directly from the wheels, rails and undercar area can be expected to de-crease by 12 dBA at 50-feet. However, as shown in Figure 3.1 and discussed in Section 3.2.1, noise is also radiated from the vibrat-ing elevated structure. For older designs of steel-elevated guideways this path can predominate over the direct air-borne path. If it is assumed that the two paths participate equally in the transmission of noise due to wheel/rail interaction and that this interaction is the predominant noise source, then the overall noise reduction obtained using the barrier is only about 3 dBA, even though the direct airborne noise is reduced by 12 dBA. If, on the other hand, propulsion system noise is imagined to be 20 dBA above the wheel/rail noise (unrealistic for present systems but useful for this example), the use of the barrier would result in the full 12 dBA reduction in the overall wayside noise.

It is evident from the foregoing that noise level quantification at each receiver, showing the contribution from each major noise source via each principal path, is required for an accurate estimate of the noise reduction achievable through the application of various noise control techniques. Such a subdivision of the overall noise level into its source-path contributions is called a noise control scenario in this report. <u>It does not include noise contributions from singularities</u>. The above example also emphasizes the need to assess the effectiveness of noise control techniques by relating potential noise reduction to the specific source or path which is affected by that technique. This type of description of noise control techniques is contained in Section 3.2.3.

The concept of combining acoustically similar segments of a rapid transit line into noise control groups was discussed at the end of Section 3.2.1. It was also noted there that the fundamental assumption underlying this division of the continuous line into a number of segments was "that sources, paths, and receivers can be approximated by some average values over each segment." The concept of noise control scenarios is simply the quantification of these average values. Thus, one noise control scenario is required for each noise control group.

Table 3-2 is an illustration of a possible scenario for the example shown in Figure 3-1. In this illustration, the average maximum pass-by noise level at the average nearest wayside residence is 90 dBA. This overall level results from the combination of the

TABLE 3-2. A SAMPLE SCENARIO FOR COMMUNITY NOISE

PATH	OVERALL PATH CONTRIBUTION	SOURCE CONTRIBUTION (dBA) RAIL JOINTS	RAIL ROUGH	WHEEL ROUGH	POWER PICKUP	PROPULSION	AUX
DIRECT AIRBORNE FROM UNDER CAR TO COMMUNITY (PATH 1)	84	82	76	76	60	69	60
STRUCTUREBORNE INTO ELEVATED STRUCTURE, THEN AIRBORNE TO COMMUNITY (PATH 2)	89	87	81	81	-	-	-
TOTAL (dBA)	90	88	82	82	60	69	60

NOTE: NUMERICAL VALUES SHOW CONTRIBUTION (IN dBA) OF EACH SOURCE VIA EACH PATH TO THE NOISE LEVEL AT WAYSIDE WHEN TRAIN PASSES BY. SCENARIOS MUST BE DETERMINED FOR ALL SEGMENTS TO COVER THE ENTIRE TRANSIT SYSTEM.

sound power propagating from each of the six sources identified in this scenario via one or both of the paths shown in the Table.

Ideally, on-site diagnostic measurements should be performed to quantify the primary contributions by source and path. For a situation as complex as the rapid transit noise environment, this ideal is currently pushing the state-of-the-art of acoustic measurement and data reduction technology. At best, one can hope to make sufficiently detailed measurements and appropriate simplifications to estimate the two or three primary source-path contributions to the overall noise level. Even that may be difficult, for instance, when one is trying to quantify the contributions due to the various possible sources of wheel/rail noise such as wheel roughness, rail roughness and joints.

In order to simplify the task of determining the scenarios for the noise control groups, the following information can be of use.

a. Published results on the relative contribution of the predominant noise sources on existing rail transit systems[2-8].

b. Diagnostic data from previous field studies[3-7].

c. Documentation of the effects of various noise control treatments on existing systems[5-15].

This data is often confusing and can appear contradictory, particularly with respect to the effectiveness of noise control techniques. These apparent contradictions are often a result of failing to take into account all the major source-path contributors to the overall noise problem. The discussion at the beginning of this Section, on the use of a barrier on elevated structures, can be seen as an apparent contradiction if all noise propagation paths are not properly considered.

Apparent contradictions can also result from not considering all noise sources. Grinding of continuously welded rail may not solve a noise problem since wheels with flats and rough spots may still produce appreciable noise on smooth ground rail.

In developing scenarios simplifying assumptions must be made on the predominant noise sources and paths and their likely relative contributions for a given noise situation. A limited number of noise measurements can then be used to reduce the uncertainties in these major source-path contributions. This is discussed further in Section 3.3 where this methodology is applied to the MBTA system.

It is important to point out that a given scenario cannot be universally applied to different systems even though the track type and condition, and vehicle operation appear similar. This is due in large part to the variations in designs and conditions of the car fleets. *Measurements must be made to identify the primary sources and paths and verify similarity to previous studies if data from the literature is to be used with confidence.*

3.2.3 Noise Control Techniques

The discussion in the previous Section demonstrates the need for detailed information on the noise reduction capabilities of various noise control techniques. Specifically, the effect of each noise control technique on each noise source and/or noise path should be known. In addition, the costs associated with each technique and any use-constraints must be known in order to formulate minimum-cost noise control strategies.

There are considerable data on specific applications of rapid transit noise control techniques[5-15]. These data were used to estimate the effectiveness of the various techniques against specific rapid transit noise sources and paths. In addition, cost data were obtained through private communications with transit system personnel[16] and acoustical consultants[17]. Tables 3-3 and 3-4 present a summary of these data for noise control techniques applied to the transit car (car treatments) and the rapid transit guideway (line treatments) respectively. Not all possible techniques have been listed. However an effort has been made to cover the most effective and commonly used techniques. Noise reduction potentials indicated apply only to the sources and paths designated.

The cost figures are estimates of the direct labor and materials expense only, and exclude professional services, overhead and other costs because that information was not readily available. Costs are divided into initial and maintenance components. For the car treatments, these costs are given per car. For the line treatments, the cost is per foot of double track (4 rails). Present indications are that cost figures in Tables 3-3 and 3-4 are low and that actual costs vary from city to city. *Use of the cost data in these tables is therefore not recommended for actual application.* The data can serve, however, as a first-order input to demonstrate the cost minimization method.

3.2.4 Determination of Minimum-Cost Noise Control Options

After defining the noise problem (in terms of scenarios and noise singularities) and the available individual noise control

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

ABATEMENT TECHNIQUE	NOISE SOURCE OR PATH AFFECTED	REDUCTION POTENTIAL	INITIAL COST	MAINTENANCE COST	REMARKS
DAMPED WHEELS	Wheel Squeal Roar (due to wheel & rail roughness Impact (due to joints & wheel flats)	Eliminates Source 1 dBA 1 dBA	$800/car ($100/wheel for adding damping to existing wheel)	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.
RESILIENT WHEELS	Wheel Squeal Roar (due to wheel & rail roughness Impact (due to joints & wheel flats)	Eliminates Source 2 dBA 2 dBA	$4000/car ($500/wheel for new wheels)	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.
INTERIOR CAR ABSORPTION	Reverberant level in car	3 dBA	$1000/car ($2/ft.^{2} x 500 ft.^{2} -floor or ceiling area)	Assumed negligible	a) Vandalism may be a problem b) Effectiveness of treatment may deteriorate if material becomes clogged with dirt c) Limited tests needed to choose material and method of application.
ACOUSTIC SEALING OF CAR (improved door seals, ventilation duct liring)	Lower car body transmission loss Upper car body transmission loss	5 dBA 10 dBA	$100/car (estimate)	Assumed negligible	a) Testing needed to determine best method and material for "sealing" car.
WHEEL TRUING	Impact (due to wheel flats) Roar (due to random wheel roughness	Eliminates Source 5-7 dBA	$250,000 (purchase and installation of wheel truing machine)	$100/car once/year ($25/wheel set x 4 wheel sets/car)	a) Can reduce wear on rails b) Increases life of wheels

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

The costs given in this Table include only direct labor and materials

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

ABATEMENT TECHNIQUE	NOISE SOURCE OR PATH AFFECTED	REDUCTION POTENTIAL	INITIAL COST	MAINTENANCE COST	REMARKS
DOOR MECHANISM-repair and maintenance	Mechanical noise from door operation	10 dBA	$600/car $100/door x 6 doors/car-estimate	$30/car/year	a) Requires investigation into causes of noisy door operation
AIR BRAKE VENT MUFFLERS	Venting of air from brake air compressors	15 dBA	$50/car	None	
NEW CAR: a. Interior Car Absorption b. Acoustical Sealing of Car Openings c. Trued Wheels d. Improved Door Mechanism Design e. Air Brake Vent Mufflers f. Double-pane Windows g. Car Wall Panel Damping h. Improved Motor/ Gear Design i. Vibration Isolation of Auxiliary Equipment j. Improved Vehicle Suspension k. Acoustical Isolation	Reverberent level in car Overall car body transmission loss Wheel flats & random roughness Mechanical noise from door operation Air venting from brakes Overall car body transmission loss Structure borne noise Propulsion system noise Structure borne noise Structure borne Noise Auxiliary & propulsion airborne noise	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 for Items c and d same as for Wheel Truing (first sheet of this table) and Door Mechanism (above), respectively.	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.
REDUCE VEHICLE SPEED	Wheel/Rail Noise Sources (Impact and Roar) Propulsion Noise	9dBA/halving of speed (average of wheel/rail and propulsion noise)	None	None	a) May only be practical on short stretches of track

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

The costs given in this Table include only direct labor and materials

TABLE 3-4. RAPID TRANSIT NOISE ABATEMENT TECHNIQUES LINE TREATMENT (1 of 2)

ABATEMENT TECHNIQUE	NOISE SOURCE OR PATH AFFECTED	REDUCTION POTENTIAL	INITIAL COST (PER DOUBLE TRACK FOOT)	MAINTENANCE COST (PER DOUBLE TRACK FOOT)	REMARKS
WELDED RAIL	Impact at Rail Joints	Eliminates Source	$25/ft. ($250/joint x 1 joint/39 ft x 4 rails/double track)	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.
IMPROVED JOINTS (bolted-epoxy joints)	Impact at Rail Joints	5 dBA	$5/ft. ($50/joint)	None	a. Can be used wherever welded rail is incompatible with system
RAIL GRINDING	Roar (Due to Rail Roughness) Soilborne Vibrations	2 (New Rail) 8 (Corrugated Rail) dBA	-	$2/ft./year ($.25/ft./track x 2 tracks x 4 times/year)	a. Does not decrease life of rail due to excessive wear
RAIL LUBRICATION	Wheel Squeal	15 dBA	$4000/curve (estimate)	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.
ADJUSTMENT OF TRACK GEOMETRY	Ride Comfort Flange Impact	- 5 dBA (Estimate)	-	$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.
RESILIENT RAIL FASTENERS	Soilborne Vibrations; Secondary Radiation from Elevated Structures	5 dBA 10 dBA	$8/ft. ($2/fastener, 2 ft. spacing; $4/ft. labor)	None	a. Use primarily with concrete ties or direct fixation to concrete invert.

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

The costs given in this Table include only direct labor and materials

TABLE 3-4. RAPID TRANSIT NOISE ABATEMENT TECHNIQUES LINE TREATMENT (2 of 2)

ABATEMENT TECHNIQUE	NOISE SOURCE OR PATH AFFECTED	REDUCTION POTENTIAL	INITIAL COST (PER DOUBLE TRACK FOOT)	MAINTENANCE COST (PER DOUBLE TRACK FOOT)	REMARKS
RESILIENTLY MOUNTED CONCRETE SLAB	Soilborne Vibrations	15-20 dBA	$300/ft. (estimate)	None	a. Used at locations requiring special treatment for soilborne vibrations. b. Design of "floating" slabs is still being perfected.
BARRIERS: NON-ABSORPTIVE ABSORPTIVE	Direct Radiation to Community	 10-14 dBA 12-16 dBA	(4 5 ft barriers/ double track) $80/ft. ($4/ft^2) $100/ft. ($5/ft^2)	 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.
DAMPING OF STEEL ELEVATED STRUCTURES	Secondary Radiation from Elevated Structures	8-12 dBA	$100/ft (estimated)	None	a. Added weight may endanger structure
ABSORPTIVE TREATMENT IN TUNNELS a. SIDE WALLS b. CONCRETE INVERT c. BOTH (a & b)	Reverberant Level Outside Car	 5 dBA 5-9 dBA 10-12 dBA	Divided Tunnel 4 ft. high on 4 walls Undivided Tunnel: 8 ft. high on 2 walls $32/ft. ($2/ft^2) $18/ft. $50/ft.	Negligible	a. Absorptive treatment should be water resistant and noncombustible
STATION TREATMENT 1. ABSORPTION: a. CEILING b. WALLS c. UNDER PLATFORM d. CONCRETE INVERT 2. ABSORPTIVE BARRIERS BETWEEN TRACKS	 1. Reverberant Level in Station 2. Reverberant Level in Station Direct Radiation to Opposite Platform	(assumes station configuration with tracks between platforms) 1a. 7 dBA 1b. 5 dBA 1c. 3 dBA 1d. 5-7 dBA 2. 5 dBA 12-16 dBA	1. a. $160/ft. (40 ft. wide) } $4/ft^2 b. $64/ft. (8' high, 2 walls) } $4/ft^2 c. $16/ft (4' high, 2 platforms) } $4/ft^2 d. 18/ft. (4 1/2' wide, 2 tracks) } $4/ft^2 2. $25/ft. (5' high, $5/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.

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

The costs given in this Table include only direct labor and materials

techniques and unit costs, the task of fitting the techniques to the problem in a way which satisfies the noise control goals at minimum cost remains.

A variety of resource allocation strategies for noise reduction could be followed. 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.

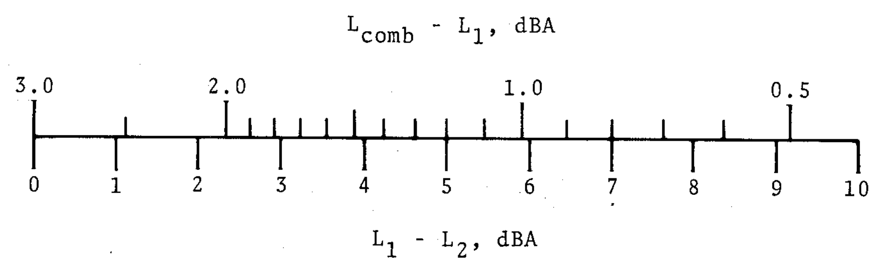
All the strategies discussed in this Report assume that noise singularities (i.e., those not included in the scenarios) are treated independently in the initial stage of the general cost analysis methodology and represent an initial expense to be added to the costs of further abatement. Once these singularities have been eliminated or at least reduced to a level below the abatement goal, reduction of the scenario noise levels can be considered. Regardless of the strategy chosen there must be a way of estimating the overall reduction in noise level and the costs involved in implementing various combinations of available noise control techniques in a given noise control situation. Noise control information of the type included in Tables 3-3 and 3-4, together with a scenario description of a noise control situation, are sufficient for computing the desired noise reduction and cost estimates. A tradeoff can then be performed to determine the minimum cost combination of railcar techniques and fixed location line techniques which together achieve a parametric goal, i.e., 85 dBA, along the entire line. The steps involved in this computation are:

a. Calculate, for each group of track segments, overall noise level estimates based on attenuating one or more sources or paths in the associated scenario by various combinations of noise control techniques.

b. Calculate estimated cost for each combination of techniques applied to the groups of segments.

c. Determine, by means of an iterative process, (see Appendix B) the total line cost to achieve each goal for reduced levels of noise at the receiver locations, using the lowest-cost combinations of techniques.

Table 3-5 is an illustration of a work sheet in which steps (a) and (b) have been applied to the scenario shown in Table 3-2. This scenario is repeated in Table 3-5 as the double row of numbers to the right of "Scenario C5" in the Noise Control Technique column. The next double row of numbers to the right of "(A) Welded Rail", illustrates the computation for the reduced overall noise level obtained by replacing the jointed rail by continuously welded rail. Table 3-4 indicates that this technique eliminates rail joint noise. This is accounted for in the work sheet by simply eliminating rail joints as a noise source. The resulting overall noise level is then computed by combining the remaining noise source contributions via each of the two transmission paths and then combining the two path totals. This "summing" process is the addition of the energy represented by the given sound pressure levels and is performed by adding two levels at a time according to the nomograph shown in Figure 3-2. Thus, the noise level due to direct airborne propagation (path 1, Table 3-5) is: 76 dBA + 76 dBA + 60 DBA + 69 dBA + 60 dBA = 79.5 dBA (where the levels are combined two at a time as explained in Figure 3.2). The noise



Note: $L_1 > L_2$, $L_{comb} = (L_{comb} - L_1) + L_1$

EXAMPLE: $L_1 = 84$ dBA, $L_2 = 79$ dBA

SOLUTION: a) $L_1 - L_2 = 5$ dBA

b) FROM GRAPH: $(L_{comb} - L_1) = 1.2$

c) $L_{comb} = 1.2 + 84 \approx 85$ dBA

NOTE: If more than two sound pressure levels are to be combined, combine the first two as illustrated above, then combine the third with the first result, and so forth.

Figure 3-2. Nomograph for Addition of Sound Pressure Levels

TABLE 3-5. OPTIONS AND COSTS FOR NOISE CONTROL ON ONE SAMPLE SCENARIO

Worksheet for Scenario C5: 19,000 Feet of Track, 100 Railcars

Noise Control Techniques	Cost $K	I Overall Noise Level (dBA)	Transmission Path	II Attenuated Path Contribution	III Unattenuated Path Contribution	Source Contribution (dBA): Rail Joints	Source Contribution (dBA): Rail Roughness	Source Contribution (dBA): Wheel Roughness	Source Contribution (dBA): Power Pickup	Source Contribution (dBA): Propulsion	Source Contribution (dBA): Auxiliary
Scenario C-5	0	90	(1) Airborne	84	84	82	76	76	60	69	60
			(2) Structureborne	89	89	87	81	81	-	-	-
(A) Continuous Welded Rail	470	85	(1)	79	79	-	76	76	60	69	60
			(2)	84	84	-	81	81	-	-	-
(B) Resil. Fasteners	150	85	(1)	84	84	82	76	76	60	69	60
			(2)	79	89	87	81	81	-	-	-
(C) Trued Wheels (D) Ground Rails	480	88	(1)	83	83	82	70	70	60	69	60
			(2)	87	87	87	76	76	-	-	-
(C) Trued Wheels (D) Ground Rails (F) Epoxy Joints	570	85	(1)	79	79	77	70	70	60	69	60
			(2)	84	84	82	76	76	-	-	-
(B) + (C) + (D) + (F)	730	80	(1)	79	79	77	70	70	60	69	60
			(2)	74	84	82	76	76	-	-	-

Note: This table shows the calculations required to estimate the cost and noise level resulting from application of various noise control techniques to the scenario of Table 3-2. The calculation for resilient fasteners for example, illustrates that structureborne path is attenuated by an estimated 10 dBA. Overall noise level is reduced only 5 dBA owing to direct airborne path.

level due to radiation from the elevated structure (path 2, Table 3-5) is: 81 dBA + 81 dBA = 84 dBA. The overall resulting noise level is the "sum" of the path contributions or about 85 dBA. This represents a 5 dBA reduction in the overall noise level when bolted joints are eliminated.

This computation is repeated for various combinations of noise control techniques. One further useful example illustrating the computation for a path attenuating technique is that for resilient rail fasteners. Table 3-4 indicates that resilient fasteners can reduce the structureborne path by 10 dBA. Since none of the noise sources are affected, Column III in Table 3-5 remains unchanged. However, Column II accounts for the 10 dB reduction in the structureborne path (path 2). The resulting overall noise level (Column I) is then the sum of the path contributions, i.e., 84 dBA + 79 dBA = 85 dBA, which represents a 5 dBA overall reduction in the wayside noise level.

The cost associated with a given technique or combination of techniques will depend on the length of track being treated (for line treatments), the number of cars being treated (for car treatments) and the period of time considered for maintenance purposes. The abatement costs given in Table 3-5 are obtained by applying the cost figures given in Tables 3-3 and 3-4 to the length of double track (19,000 ft.) and number of cars (100) included in the sample scenario. The costs include maintenance for a 10 year period.

A variety of strategies could be followed to allocate resources for noise reduction. The use of a single sample stragegy is discussed below. The noise control strategy starts with the question, "How much will it cost to reduce the present rail transit system noise levels to levels of 90, 85, 80, and 75 dBA in the residential community throughout the entire transit system?" (Similar questions can be posed for noise in cars and in stations).

Once the computations such as those shown in Table 3-5 have been carried out for all scenarios (hence all track) on a transit line, a tradeoff (generally requiring some iteration) can be performed to determine the combination of railcar techniques and fixed location line techniques which together achieve a parametric goal (e.g., 85 dBA) at minimum cost. Sample results of such calculations are illustrated in Table 3-6. This is, in effect, the answer to the second question posed in the introduction: "What is the least costly way to reduce a system's noise output to a specified level?" For each rapid transit community noise goal, the scenario whose track segments and cars must be modified and the noise control techniques which are estimated to achieve the goal at the minimum cost shown, are listed.

The three steps of the methodology described in this Section (Steps (a) - (c) at the beginning of this Section) can be performed manually, as was done in the MBTA pilot application. However, this is time-consuming and therefore a computer program to perform the steps from tabulated inputs of scenarios, noise control technique data, and abatement goals has been developed. The algorithm upon which this computer program is based is given in Appendix B.

3.3 MBTA MINIMUM COST NOISE CONTROL

The results summarized in this Section were obtained by application of the methodology described in Section 3.2 to the three rapid transit lines of the MBTA System. *To emphasize the preliminary nature of the results obtained from applying the first-order methodology, costs, based on data like that in Tables 3-3 and 3-4, were expressly calculated in undefined "cost units" proportional to the dollar costs.*

This Section is organized in a fashion similar to that of Section 3.2. The predominant noise sources and paths for each noise control group of the MBTA system (See Tables 2-1 through 2-4) are identified and quantified into noise control scenarios. By an iterative application of the noise control techniques described in Tables 3-3 and 3-4, the combination of techniques which reduce the overall noise levels along each line to the parametric goals of 90, 85, 80, and 75 dBA were determined. This was done separately for each of the receivers: the rider in the car, the patron on the station platform, and the resident along the wayside. Finally,

TABLE 3-6. MINIMUM COST COMMUNITY NOISE CONTROL FOR MBTA ORANGE LINE

DESIRED LEVEL (dBA)	SCENARIO	NOISE CONTROL TECHNIQUES	TOTAL COST UNITS
90	C4 C4, C5	RESILIENT FASTENER TRACK ADJUSTMENTS DAMPED WHEELS	40
85	C4 C4, C5	WELDED RAIL TRACK ADJUSTMENTS DAMPED WHEELS RESILIENT FASTENERS	240
80	C4 C4, C5	GROUND RAIL TRUED WHEELS TRACK ADJUSTMENTS DAMPED WHEELS RESILIENT FASTENERS WELDED RAIL	750
75	C4 C4, C5	BARRIER (NON-ABSORPTIVE) TRACK ADJUSTMENTS DAMPED WHEELS RESILIENT FASTENERS GROUND RAIL TRUED WHEELS WELDED RAIL	1410

NOTE: METHODOLOGY REQUIRES COST AND NOISE LEVEL ESTIMATES SUCH AS SHOWN IN TABLE 3-5 TO BE DETERMINED FOR ALL SCENARIOS (HENCE ALL TRACK) ON A TRANSIT LINE. TOTAL COST ESTIMATES ARE CALCULATED AND THE COMBINATION OF NOISE CONTROL TECHNIQUES HAVING THE LEAST SYSTEM COST IS SELECTED.

an estimate was made of the combination of techniques which would reduce the noise levels to the above goals simultaneously for all three receivers for each line of the MBTA system. Regardless of whether the receivers were considered separately or simultaneously, the initial step in the abatement strategy was the elimination or reduction of the noise singularities, i.e., those noise sources not considered in the scenarios.

3.3.1 MBTA Noise Control Scenarios

A number of noise sources and propagation paths were identified for the in-car, station and wayside receivers of the MBTA system. The sources included wheel/rail noise sources, propulsion and auxiliary equipment noise, and power pickup noise. The paths included combinations of direct airborne noise, structureborne noise and reverberant noise. In all, five paths were identified for the in-car noise, three for the station noise, and two for the wayside noise.

Ideally, on-site diagnostic measurements should have been performed to quantify the primary source and path contributions. The measurements made to define the noise output of the MBTA system in this first-order study did not quantify individual source or path contributions. Diagnostic data from previous studies [2-15], A-weighted sound levels from the MBTA measurements, MBTA track construction data, and engineering judgement was therefore used to determine the numerical values in the scenarios.

Tables 3-7, 3-8 and 3-9 give the scenarios for the in-car, station, and residential wayside receivers, respectively. The actual value of each source-path contribution to the overall noise level is, by virtue of the methods used, subject to a large degree of uncertainty. Because of this uncertainty and also because of the specific application to the MBTA system, *the values of the source-path contributions in Tables 3-7 through 3-9 should not be generalized for other systems.* They are sufficient, however, for a first-order assessment of abatement requirements for the MBTA system.

TABLE 3-7. SCENARIOS FOR IN-CAR NOISE LEVELS (1 of 3)

Scenario	Total Plateau Level (dBA)	Path Contri- bution	Path*	Scenarios for In-Car Noise Levels Source Noise Levels (dBA) Wheel Flats	Rail Joints	Rail Rough- ness	Wheel Rough- ness	Power Pickup	Propul- sion	Aux. (Mech)	Aux. (Aero)		Line Element
R1	95	95	All		93	87	87	71	80	68	65		Tunnel
		86	P1		85	73	73	56	77	68	-		
		94	P2		92	87	87	70	77	-	-		
		81	P3		79	73	73	65	-	-	-		
		65	P5		-	-	-	-	-	-	65		
R2	90	90	All		88	82	82	66	75	68	65		Tunnel
		81	P1		80	68	68	51	72	68	-		
		89	P2		87	82	82	65	72	-	-		
		76	P3		74	68	68	60	-	-	-		
		65	P5		-	-	-	-	-	-	65		
R3	85	85	All		83	77	77	61	70	68	65		Tunnel
		77	P1		75	63	63	46	67	68	-		
		84	P2		82	77	77	60	67	-	-		
		71	P3		69	63	63	55	-	-	-		
		65	P5		-	-	-	-	-	-	65		

* Path Definitions

P1 = Pa+Pb
P2 = Pc+Pd+Pb
P3 = Pe+Pd+Pb
P4 = Pg+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
Pg = Secondary radiation to car exterior

TABLE 3-7. SCENARIOS FOR IN-CAR NOISE LEVELS (2 of 3)

Scenarios for In-Car Noise Levels													
				Source Noise Levels (dBA)									
Scenario	Total Plateau Level (dBA)	Path Contri-bution	Path*	Wheel Flats	Rail Joints	Rail Rough-ness	Wheel Rough-ness	Power Pickup	Propul-sion	Aux. (Mech)	Aux. (Aero)		Line Element
R4	80	80	All		78	72	72	56	65	68	65		Tunnel
		73	P1		70	58	58	41	62	68	-		
		79	P2		77	72	72	55	62	-	-		
		66	P3		64	58	58	50	-	-	-		
		65	P5		-	-	-	-	-	-	65		
R5	85	85	All		83	76	76	63	73	68	65		At-Grade
		82	P1		81	69	69	52	73	68	-		
		80	P2		78	73	73	56	63	-	-		
		77	P3		75	69	69	61	-	-	-		
		65	P5		-	-	-	-	-	-	65		
R6	80	80	All		78	71	71	58	68	68	65		At-Grade
		78	P1		76	64	64	47	68	68	-		
		75	P2		73	68	68	51	58	-	-		
		72	P3		70	64	64	56	-	-	-		
		65	P5		-	-	-	-	-	-	65		

* Path Definitions

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

Where

Pa = Structureborne path
Pb = Interior reverberation
Pc = Exterior reverberation
Pd = Car body transmission loss
P_e = Direct radiation to car exterior
Pf = Direct field, car interior
Pg = Secondary radiation to car exterior

TABLE 3-7. SCENARIOS FOR IN-CAR NOISE LEVELS (3 of 3)

Scenario	Total Plateau Level (dBA)	Path Contri-bution	Path*	Scenarios for In-Car Noise Levels Source Noise Levels (dBA) Wheel Flats	Rail Joints	Rail Rough-ness	Wheel Rough ness	Power Pickup	Propul-sion	Aux. (Mech)	Aux. (Aero)		Line Element
R7	85	85	All		83	76	76	65	71	68	65		Elevated
		80	P1		79	67	67	50	71	68	-		&
		78	P2		76	71	71	54	61	-	-		Bridge
		72	P3		70	64	64	56	-	-	-		
		80	P4		78	72	72	64	-	-	-		
		65	P5		-	-	-	-	-	-	65		
R8	80	80	All		78	71	71	60	66	68	65		Elevated
		76	P1		74	62	62	45	66	68	-		&
		73	P2		71	66	66	49	56	-	-		Bridge
		67	P3		65	59	59	51	-	-	-		
		75	P4		73	67	67	59	-	-	-		
		65	P5		-	-	-	-	-	-	65		
R9**	80	80	All	73	76	70	70	54	65	68	65		Tunnel
		76	P1	69	72	60	60	43	64	68	-		
		77	P2	71	74	69	69	52	59	-	-		
		64	P3	58	61	55	55	47	-	-	-		
		65	P5	-	-	-	-	-	-	-	65		

* Path Definitions

P1 = Pa+Pb
P2 = Pc+Pd+Pb
P3 = Pe+Pd+Pb
P4 = Pg+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
Pg = Secondary radiation to car exterior

**Scenario R9 is for the Silverbirds running on the Red Line Scenario 2 Section

TABLE 3-8. SCENARIOS FOR STATION NOISE

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

PATH DEFINITIONS

P1 = Direct Radiation From Wheel-Rail To Listener

P2 = Station Reverberation

P3 = Secondary Radiation From Structure

TABLE 3-9. SCENARIOS FOR RESIDENTIAL WAYSIDE PASS-BY NOISE

SCENARIO	AVG. PASSBY LEVEL (dBA)	PATH CONTRIB.	SOURCE NOISE LEVELS (dBA)									CONSTRUCTION
			PATH	WHEEL FLATS	RAIL JOINTS	RAIL ROUGH	WHEEL ROUGH	POWER PICKUP	PROPUL-SION	AUX (MECH)	AUX (AERO)	
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

3.3.2 Choice of MBTA Noise Control Techniques

In order to develop a scheme for minimizing the cost of noise abatement, it is necessary to choose a time period over which costs are to be minimized. This is necessary because some abatement techniques have only an initial installation cost, some have only maintenance type costs, and other have both initial and maintenance costs. For the MBTA application, a 10 year period was chosen, over which noise abatement costs were to be minimized. In performing this cost minimization, it was assumed that maintenance occurs over short time intervals beginning immediately at the start of the abatement program. Computed abatement levels apply after maintenance has been performed. Inflation has been neglected.

To obtain gross cost estimates, two abatement strategies were considered. Both assume that 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 general cost analysis methodology and represent a base cost to be added to the costs of further abatement. Table 3-10 gives the

TABLE 3-10. BASE COSTS (IN COST UNITS) FOR ELIMINATION OF NOISE SINGULARITIES ON THE MBTA

TREATMENT \ LINE	TREATMENT COSTS(COST UNITS) 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

base costs (in unspecified cost units) associated with the above techniques. The cost of each technique, applied to each of the three rapid transit lines for 10 years, is given.

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? In many instances, noise control techniques which succeed in reducing the levels in, say, the cars, would result in somewhat reduced levels elsewhere, that is, in the station and in the community. In this first strategy this effect is a fortunate bonus. The base costs computed for each receiver on each line are shown in Table 3-11. Since all the noise abatement techniques listed in Table 3-10 affect the in-car noise, the total base cost for the rider is the same as the total base cost considering all receivers.

TABLE 3-11. BASE COSTS (IN COST UNITS) ASSOCIATED WITH EACH RECEIVER

RECEIVER \ LINE	TOTAL BASE COST (COST UNITS) TO EACH RECEIVER		
	BLUE	ORANGE	RED
RIDER (TECHNIQUES 1-4 FROM TABLE 3-10)	303	379	672
STATION (TECHNIQUES 1,3,4 FROM TABLE 3-10)	192	255	383
COMMUNITY (TECHNIQUES 1&2 FROM TABLE 3-10)	231	284	558
ALL RECEIVERS (TECHNIQUES 1-4 FROM TABLE 3-10)	303	379	672

The minimum costs for abatement, excluding the base costs and considering one type of receiver at a time, were computed for the Blue, Orange, and Red Lines, and are shown in Tables 3-12, 3-13, and 3-14 respectively. Different levels of abatement and the necessary techniques to minimize costs are shown. The normalized costs shown on these tables are defined and discussed in Section 3.3.3.

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 for all three classes of receivers? Table 3-15 shows the minimum cost abatement options resulting from the second abatement strategy. In general, adding the costs from Tables 3-12, 3-13, and 3-14 to attain rider, station, and community target noise levels would be overly conservative for two reasons. First the cost for a given technique applied to the car or to a specific track segment should be counted no more than once. This has been taken into account in Table 3-15 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.

The total minimum costs (in cost units) required to achieve the parametric abatement goals are obtained by adding the base costs from Table 3-11 to the minimized costs given in Tables 3-12 through 3-15. The results are summarized in Figure 3.3 where the cost of abatement has been plotted against abatement goal for each receiver considered independently and for all receivers considered simultaneously.

3.3.3 Normalized Cost

Normalized cost (C_n) is a measure of cost which was developed in this Study in anticipation of two future needs:

TABLE 3-12. MINIMUM COST NOISE ABATEMENT ON THE MBTA BLUE LINE - INDEPENDENT RECEIVERS (1 of 3)

RECEIVER / DESIRED LEVEL (dBA)	RIDER			
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT.
90	R1	Seal Car	75	3.0
85	R1,R2	Seal Car, Interior Car Absorption	150	2.3
80	R1 R1, R2, R3, R5	Weld Rail Seal Car, Interior Car Absorption	274	1.3
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

NOTES: (a) The base costs for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.

(b) Refer to Tables 2-1, 2-3 and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.

(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-12. MINIMUM COST NOISE ABATEMENT ON THE MBTA BLUE LINE - INDEPENDENT RECEIVERS (2 of 3)

RECEIVER / DESIRED LEVEL (dBA)	STATION			
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT.
90	-	-	NONE	-
85	S2, S3, S4	Weld Rail Resilient Fastener	143	8.2
	S3, S2	Under Platform Treatment		
80	S2, S3, S4 S6, S7	Weld Rail Resilient Fastener	359	9.6
	S2, S3	Under Platform Treatment		
	S2, S4, S6, S7	Barrier		
	S3	Grind Rails		
	S2, S3	Wall Treatment		
75	S2, S3 S4, S6 S7	Weld Rail Resilent Fastener	567	9.8
	S2, S3, S4	Under Platform Treatment		
	S2, S3, S4	Barrier		
	S3, S4	Grind Rails		
	S2, S3	Wall Treatment		
	S3	Ceiling Treatment		

NOTES: (a) The base costs for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.
(b) Refer to Tables 2-1, 2-3 and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.
(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-12. MINIMUM COST NOISE ABATEMENT ON THE MBTA BLUE LINE - INDEPENDENT RECEIVERS (3 of 3)

RECEIVER / DESIRED LEVEL (dBA)	COMMUNITY			
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA FT.
90	-	-	NONE	-
85	C1	Weld Rail	65	5.0
80	C1	Barrier (Non-Absorptive)	351	6.4
	C2	Weld Rail		
75	C1	Improve Joints	757	6.6
	C1, C2	Barrier (Non-absorptive)		
	C3	Weld Rail		

NOTES: (a) The base costs for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.
(b) Refer to Tables 2-1, 2-3 and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.
(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-13. MINIMUM COST NOISE ABATEMENT ON THE MBTA ORANGE LINE - INDEPENDENT RECEIVERS (1 of 3)

RECEIVER / DESIRED LEVEL (dBA)	RIDER			
	SCENARIO NUMBER (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT.
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
75	R2,R7 R3 R2,R3, R4, R7, R8	Weld Rail Improve Joints Seal Cars Interior Car Absorption	424	2.1

FOOTNOTES:
(a) The base costs, for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.
(b) Refer to Tables 2-1, 2-3 and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.
(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-13. MINIMUM COST NOISE ABATEMENT ON THE MBTA ORANGE LINE - INDEPENDENT RECEIVERS (2 of 3)

RECEIVER / DESIRED LEVEL (dBA)	STATION			
	SCENARIO NUMBER (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT.
90	-	-	NONE	-
85	-	-	NONE	-
80	S5,S9 S10,S11, S10 S5,S9,S11	Weld Rail Resilient Fastener Grind Rail Barrier	206	10.3
75	S5,S9 S10,S11, S12,S13, S14 S5,S9,S11 S12 S5,S9,S11	Weld Rail Resilient Fastener Grind Rail Barrier Under Platform Treatment True Wheels	636	11.6

FOOTNOTES: (a) The base costs, for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.
(b) Refer to Tables 2-1, 2-3 and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.
(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-13. MINIMUM COST NOISE ABATEMENT ON THE MBTA ORANGE LINE - INDEPENDENT RECEIVERS (3 of 3)

RECEIVER	COMMUNITY			
DESIRED LEVEL (dBA)	SCENARIO NUMBER (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT.
90	C4	Resilient Rail Fasteners	14	1.5
85	C4 C4,C5	Weld Rail Resilient Rail FASTENERS	212	1.9
80	C4,C5 C4	Weld Rail Resilient Rail Fasteners Grind Rails, True Wheels	725	3.3
75	C4 C4,C5 C4,C5, C6	Barrier (Non-Absorptive Weld Rail, Grind Rail, True Wheels Resilient Rail Fasteners	1386	4.2

FOOTNOTES:
(a) The base costs, for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.
(b) Refer to Tables 2-1, 2-3 and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.
(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-14. MINIMUM COST NOISE ABATEMENT ON THE MBTA RED LINE - INDEPENDENT RECEIVERS (1 of 3)

RECEIVER / DESIRED LEVEL (dBA)	RIDER			
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT
90	-	-	NONE	-
85	R2	Seal Cars	92	1.2
80	R2, R3, R5	Seal Cars, Interior Car Absorption	184	.8
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

FOOTNOTES:
(a) The base costs for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.
(b) Refer to Tables 2-1, 2-3, and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.
(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-14. MINIMUM COST NOISE ABATEMENT ON THE MBTA RED LINE - INDEPENDENT RECEIVERS (2 of 3)

RECEIVER	STATION			
DESIRED LEVEL (dBA)	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT
90	S1	Weld Rail Resilient Fasteners	20	6.8
85	S1, S2; S3 S1	Weld Rail Resilient Fastener Barrier	127	6.6
80	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	443	8.9
75	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 Treat-ment True Wheels	997	12.5

FOOTNOTES: (a) The base costs for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.

(b) Refer to Tables 2-1, 2-3, and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.

(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-14. MINIMUM COST NOISE ABATEMENT ON THE MBTA RED LINE - INDEPENDENT RECEIVERS (3 of 3)

RECEIVER / DESIRED LEVEL (dBA)	COMMUNITY			
	SCENARIO # (b)	ABATEMENT TECHNIQUES	TOTAL COST (a) (COST UNITS)	NORMALIZED COST (c) COST UNITS/dBA-FT
90	-	-	NONE	-
85	C1 C5	Weld Rail Resilient Rail Fasteners	94	4.6
80	C1 C2, C5 C5 C7, C8	Barriers (Non-Absorptive) Weld Rail Resilient Rail Fasteners True Wheels (Silver Birds Only)	448	2.7
75	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

FOOTNOTES:
(a) The base costs for elimination of noise singularities are not included in this table. These costs are identified in Table 3-11.
(b) Refer to Tables 2-1, 2-3, and 2-4 for identification of the track segments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.
(c) The normalized cost is defined and explained in Section 3.3.3.

TABLE 3-15. MINIMUM COST NOISE ABATEMENT RESULTING IN EQUAL NOISE LEVELS AT EACH RECEIVER (1 of 3)

Line	Blue			Orange			Red		
Desired Level (dBA)	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)
90	R1	Seal Car	75	C4	Resilient Fasteners	14	S1	Weld Rail, Resilient Fasteners	20
85	R1, R2	Seal Car, Interior Car Absorption	358	R2, C4	Weld Rail	221	R2	Seal Cars	313
	C1, S2, S3, S4	Weld Rail		R2	Grind Rail		C1, S1, S2, S3	Weld Rail	
	S2, S3, S4	Resilient Fasteners		C4, C5	Resilient Fasteners		C5, S1, S2, S3	Resilient Fasteners	
	S2, S3	Under Platform Treat.					S1	Barriers(c)	

Footnotes: (a) The base costs defined in Table 3-11 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. Scenario numbers are identical with the corresponding noise control group numbers.

(c) All station barriers are absorptive; all wayside barriers are non-absorptive.

TABLE 3-15. MINIMUM COST NOISE ABATEMENT RESULTING IN EQUAL NOISE LEVELS AT EACH RECEIVER (2 of 3)

Line / Desired Level (dBA)	Blue			Orange			Red		
	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)
80	R1, C2, S2, S3, S4, S6, S7	Weld Rail	984	R2, C4, C5, S5, S9, S10 S11	Weld Rail	1080	R2, R3, R5	Seal Cars Interior Car Absorption	999
	R1, R2 R3, R5	Seal Cars, Interior Car Absorption		R7	Improve Joints		C2, C5, S1, S2, S3, S9	Weld Rail	
	C1, S2 S4, S6, S7	Barriers (c)		R2, R3, R7	Seal Cars		C5, S1, S2, S3	Resilient Fasteners	
	S2, S3, S4, S6, S7	Resilient Fasteners		C4, C5 S5, S9, S10, S11	Resilient Fasteners		C1, S1, S2, S9	Barriers	
	S2, S3	Under Platform Treat.		C4, S10	Grind Rail		S7, S8	Grind Rail	
	S3	Grind Rails		C4, S10	Grind Rail		S1, S2, S3	Under Platform Treat. True Wheels	
	S2, S3	Wall Treat.		S5, S9, S11	Barriers (c) True Wheels				

Footnotes: (a) The base costs defined in Table 3-11 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. Scenario numbers are identical with the corresponding noise control group numbers.

(c) All station barriers are absorptive; all wayside barriers are non-absorptive.

TABLE 3-15. MINIMUM COST NOISE ABATEMENT RESULTING IN EQUAL NOISE LEVELS AT EACH RECEIVER (3 of 3)

Line / Desired Level (dBA)	Blue Scenario (b)	Blue Abatement Techniques	Blue Total Cost (a) (Cost Units)	Orange Scenario (b)	Orange Abatement Techniques	Orange Total Cost (a) (Cost Units)	Red Scenarios (b)	Red Abatement Techniques	Red Total Cost (a) (Cost Units)
75	R1, R2, R5, C3, C2, S3, S4, S6, S7	Weld Rail	2203	R2, R7, C4, C5, S5, S9, S10, S11, S12, S13, S14	Weld Rail	2166	R2, R5, C3, C5, S1, S2, S3, S9	Weld Rail	3479
	R3, C1	Improve Joints		R3	Improve Joints		R3, R6	Improve Joints	
	R1, S3, S4	Grind Rail		R2, R3 R4, R7 R8	Seal Cars Interior Car Absorption		R2-R6, R8	Seal Cars, Interior Car Absorption	
	R1, R2, R3, R5	Seal Car, Interior Car Absorption		C4, C5, S5, S9, S10-S14	Grind Rail, Resilient Fasteners		C8, S3, S7, S8	Grind Rails	
	C1, C2, S2, S4, S6	Barriers		C6	Resilient		C5, S1-S3, S9	Resilient Fasteners	
	S2, S3, S4, S6, S7	Resilient Fasteners		C4, S5, S9, S11, S12	Barriers		C1, C2, C5, C7, C8, S1, S2, S9	Barriers	
	S2, S3 S4	Under Platform Treat.		S5, S9, S11	Under Platform Treat. True Wheels		S1-S3, S7-S9	Under Platform Treat.	
	S2, S3	Wall Treat.					S1, S2	Wall Treat.	
	S3	Ceiling Treat. True Wheels					S1	Ceiling Treat. True Wheels	

Footnotes: (a) The base costs defined in Table 3-11 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. Scenario numbers are identical with the corresponding noise control group numbers.

(c) All station barriers are absorptive; all wayside barriers are non-absorptive.

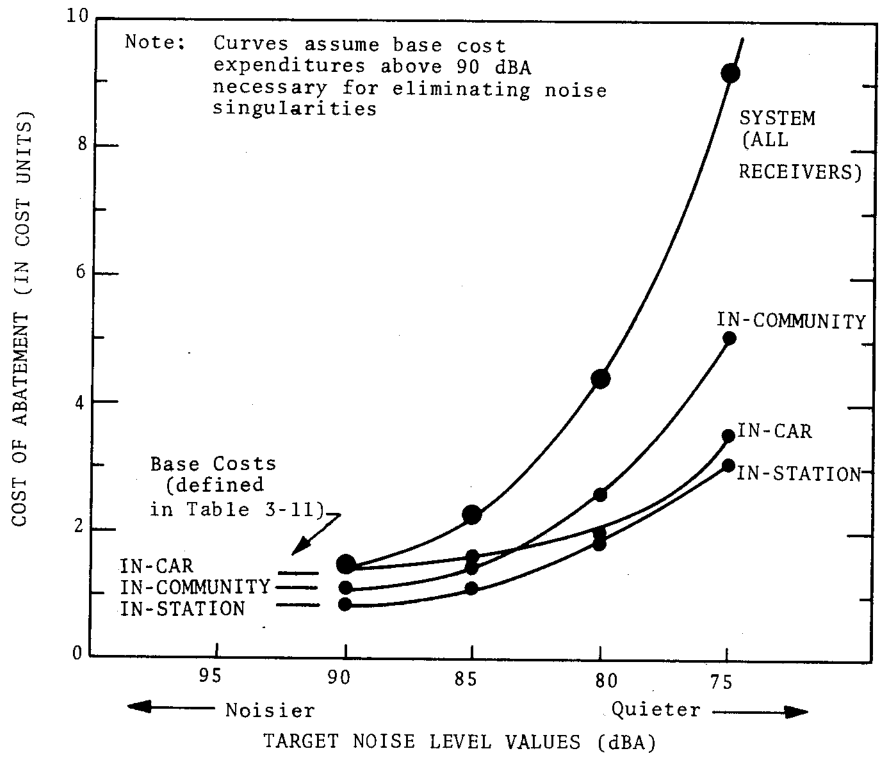


Figure 3-3. Cost of Abating the MBTA Rapid Transit System to a Specified Level (dBA) at Each Receiver

1) A simple rule-of-thumb cost estimate for a wide variety of rapid transit noise control applications.

2) A means of assessing probable cost-effectiveness of new or improved techniques.

Normalized cost (C_n) is defined by the equation

$$C_n(X) = \frac{C(X)}{\Sigma_s L_s R_s}$$

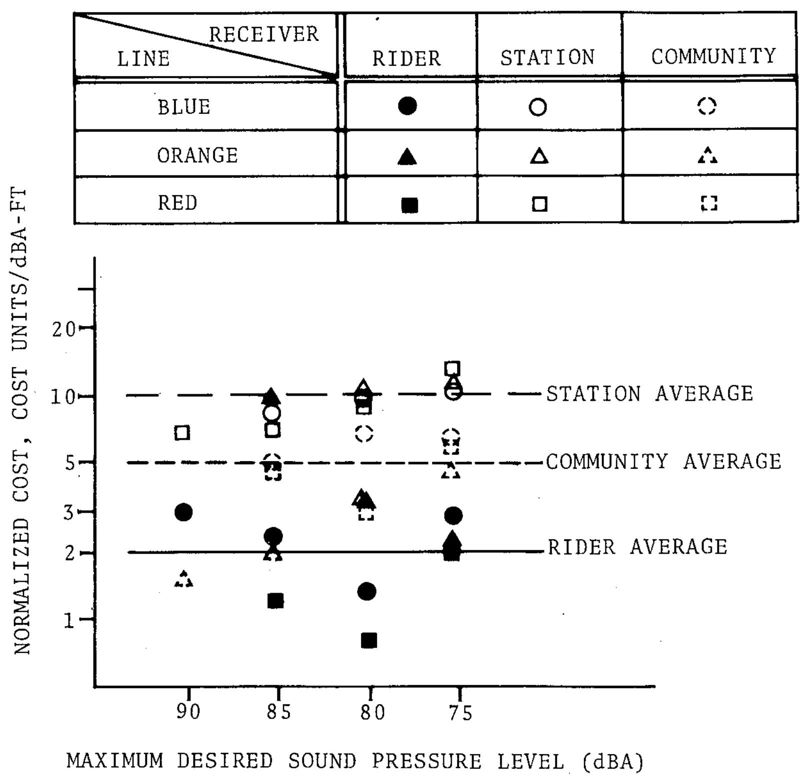
where X is the level abated to, C(X) is the total cost to abate to level X, s is the segment (or station) number, L_s is the length of the segment (or station) in feet and R_s is the reduction in dBA calculated for segment (or station) s.

Suppose the normalized cost were shown to be relatively insensitive to such factors as line length, amount of abatement desired, and age of line and equipment. Then some average value, $\overline{C}_n$, ought to be applicable to other systems directly;

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

where C(X) is the total cost to abate to some desired level.

Figure 3.4 shows the normalized cost figures (computed from the results given in Tables 3-12 through 3-14) for the three MBTA lines over a 20 dBA range of abatement. It should be noted that these normalized costs do not include the base costs associated with the elimination of the noise singularities and that they are based on minimum noise control costs. About 75 percent of the data points lie between normalized costs of 2 to 10 cost units/ft/dBA. This variation can be reduced if the three receivers are considered independently. The average normalized costs are then 2, 5, and 10 cost units/ft/dBA for rider, community, and station noise abatement respectively. These values can be used to obtain gross estimates of noise abatement minimum costs for other systems. This is done by adding engineering costs as well as Table 3-11 base costs to the values computed using the average normalized costs.



NOTE: THE NORMALIZED COST DOES NOT INCLUDE THE BASE COSTS IDENTIFIED IN TABLE 3-11.

Figure 3.4 Dependence of Normalized Cost on Desired Abatement Level

The second use for normalized cost is in assessing the probable cost-effectiveness of new or imporved techniques. Estimated costs of new techniques could be easily compared to costs of existing techniques if normalized costs are used in both cases. Such a comparison would be useful in making design and development decisions.

Limited experience to date indicates that normalized cost concept is useful. However the normalized costs resulting from the MBTA study are not adequately supported by hard cost data to be applicable to general noise abatement cost estimating at other properties. Additional work must be done at other properties to substantiate and refine the cost and abatement potential data for the various noise control techniques so that viable, normalized cost figures can be developed for use across the board.

4. SUMMARY AND RECOMMENDATIONS

A methodology has been developed to assess noise and to determine the noise control techniques and associated costs required for minimum-cost control on an urban rail rapid transit system to any selected upper limit of noise. Although needing further refinement, this new methodology provides a framework for planning and designing minimum cost noise control in rapid transit systems. The basic elements of the method can be applied, conceptually at least, to any fixed guideway transportation system.

The results of the application of this methodology to the MBTA system are summarized in Section 4.1 below. A list of recommendations for improving the methodology follows in Section 4.2.

4.1 SUMMARY OF PILOT APPLICATION TO THE MBTA SYSTEM

1. The dominant range of MBTA noise (in cars, 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 urban rail rapid transit systems in the United States.
   - Average in-car plateau levels (excluding the Silverbirds) are 87, 83, and 81 dBA for cars in tunnels, at-grade, and on elevated lines respectively.
   - The approximate average maximum station platform noise levels in tunnel, at-grade, and in elevated stations are 90,87, and 82 dBA respectively.
   - The approximate average maximum pass-by level outside the adjacent residences is 87 dBA.
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.

3. Application of the abatement methodology to the MBTA suggests that 15 to 20 dBA of urban rail transit noise reduction for wayside communities is achievable on older systems with present technology. Similar reductions are considered achievable for noise reduction in presently untreated cars and stations.

4. Approximately 15% of the total estimated cost of abatement to 75 dBA is assigned to the elimination of noise (or noise causing) singularities (wheel squeal, noisy door operation, unmuffled air brakes, and track geometry irregularities). Any large scale noise abatement program should start with a reduction of these types of noise, which are particularly annoying in view of their tonal content and/or their impulsive character.

5. Based on application to the MBTA, the normalized cost concept has been shown to be relatively insensitive to the amount of abatement desired, length of line, age of line and equipment, and so on. This implies that the concept is useful for estimating minimum costs of noise abatement on other systems. Further study is necessary to verify this possibility.

6. The overall accuracy of the MBTA results depends on the accuracy of the data in three areas:

   a. The noise level attributed to each source-path combination in the scenarios,

   b. The noise reduction estimates for specific noise abatement techniques.

   c. The cost data for these specific noise abatement techniques.

   A sensitivity analysis is required to estimate the errors in the overall abatement costs resulting from errors in (a), (b), and (c) above. In the MBTA study, existing experimental data, overall noise level measurements, and engineering judgement were used to determine the data in the three areas. Although this was adequate to develop and exercise the first-order methodology, the engineering tasks of actual noise control will require more reliable support. Such support should be obtained through experimental verification of the most important details in the scenarios and confirmation of the noise reduction potential and costs of the leading noise abatement techniques and components. Work is presently underway in each of the three areas to refine the methodology.

4.2 RECOMMENDATIONS FOR THE MEASUREMENT AND MINIMUM-COST NOISE CONTROL METHODOLOGIES

1. The statistical nature of the noise data must be considered more directly in the measurement and data reduction methodology. Confidence limits should be established to provide criteria for determining the number of in-car, station and wayside measurements required.

2. The measurement methodology should be updated to adhere to ISO[18,19] and UITP[20,21] measurement standards wherever applicable. It would also be advisable to establish a standard measurement procedure for the assessment of noise in existing rail rapid transit systems.

3. There is a fundamental question about the choice of acoustical measure used to characterize the noisiness of a rail rapid transit system. This Study chose the maximum A-weighted sound level (slow averaging) for any typical sigle event, for example, train pass-by. Obviously a more refined model can attempt to include additional parameters, such as tonal content and duration of the noise, at the expense of more complex measurement and estimating procedures. The possible need

for a more refined model shoud be considered in future efforts.

4. Diagnostic measurement techniques should be established for determining the principal source-path contributions to the receiver noise levels.

5. In the current noise control methodology, the receivers are treated independently. A method should be determined considering two or possibly all three receivers simultaneously.

6. The following items should be incorporated into the in-car noise assessment methodology.

   a. Effect of passenger density on in-car noise levels

   b. Vehicle speed

   c. Ride roughness

7. The following considerations are important for improved assessment of the station noise and require additional investigation.

   a. Noise levels in toll booths

   b. Noise measurements of trains stopping at opposite platforms or passing through stations without stopping

   c. The possibility of using only the entering maximum noise levels to characterize station noise because this is the noise to which most patrons will be exposed, (disembarking riders may be away from the platforms by the time the train departs).

   d. Measured station reverberation times appear important as diagnostic data to determine the relative contribution of reverberant and direct radiation.

8. The community noise assessment methodology should be modified to include:

   a. Groundborne vibration, particularly adjacent to subway tunnels, as a measure of the impact of urban rail transit system operation on the community.

   b. Investigations relating nearfield car exterior noise measurements (made while moving with the car) to wayside noise levels.

9. Modification of the method of computing the overall cost of abatement to account for such things as professional services and overhead costs, scheduling of noise control implementation and loss of income due to disruption of service. (Work in this area is presently underway.)

As a concluding recommendation, a clear, reasoned policy on priorities, schedules, and allocation of resources for noise abatement in urban rail rapid transit systems should be developed. 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 current absence of standards and regulations.

d. The substantial cost of noise abatement.

APPENDIX A

MBTA NOISE DATA

TABLE A-1. COMMUNITY NOISE MEASUREMENT LOCATIONS

MEASUREMENT LOCATION			Approx. Mic. Position w.r.t. Nearest Track ℄		Train Length (# of Cars)	Average Maximum Pass-By Level (dBA)
Line	Between Stations[(a)]	Site - Particulars	Horiz. Dist.(ft)	Vertical Dist.(ft.)		
Blue	10,11	at-grade track	40	5	2	89
Blue	7,8	at-grade track	50	5	4	84
Orange	2,3	elevated track	30	30	2	88
Orange	4,5	elevated track	15	5	2	100(squeal)
Orange	10,11	elevated track	55	-20[(b)]	4	94
Orange	12,13	elevated track	70	-20[(b)]	2	88
Red	4,5	elevated track	30	3	4	92
Red	10,11	at-grade track	30	5	4	88
Red	12,13	8 ft cutting	50	13	4	80
Red(SSE)[(c)]	9,15	embankment	50	-3[(b)]	4	85
Red(SSE)[(c)]	16,17	4 ft cutting	46	9	2	86

(a) Refer to Figs. A-4 through A-6 for identification of Station Numbers.

(b) Negative distance indicates microphone is below track level.

(c) South Shore Extension

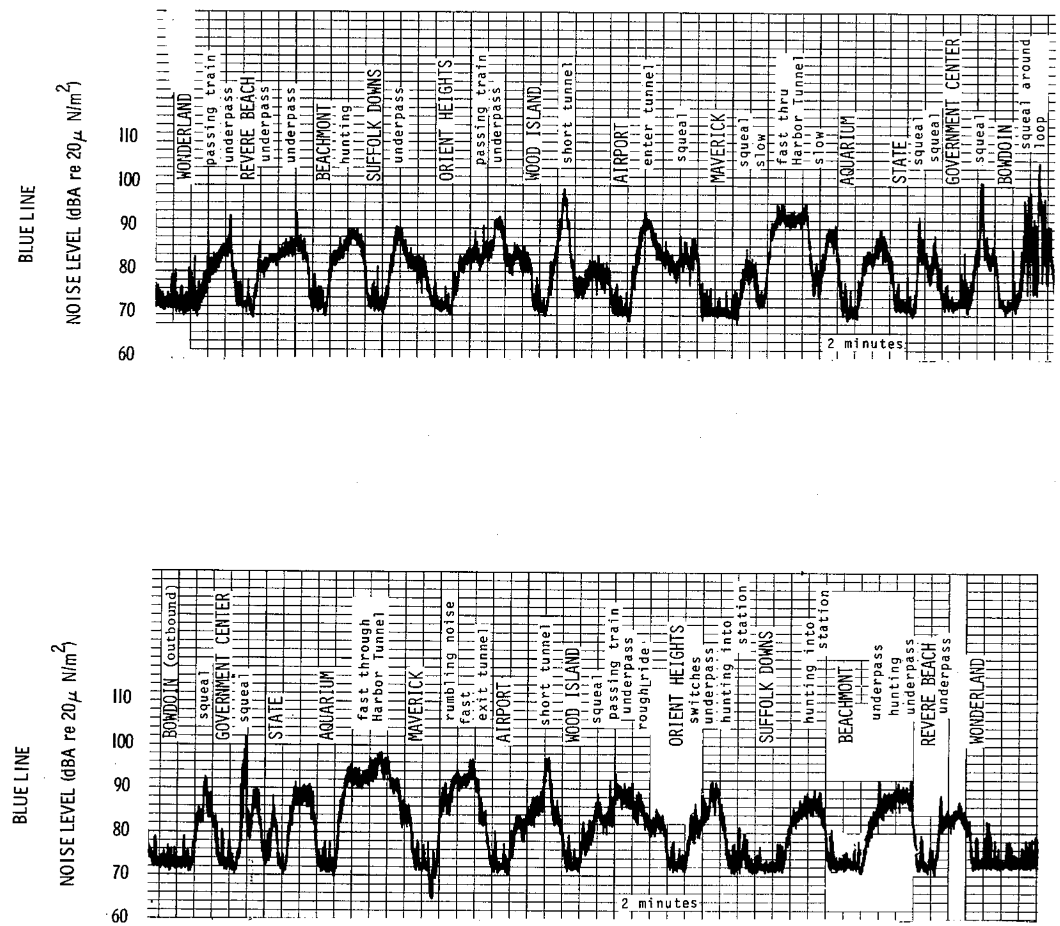
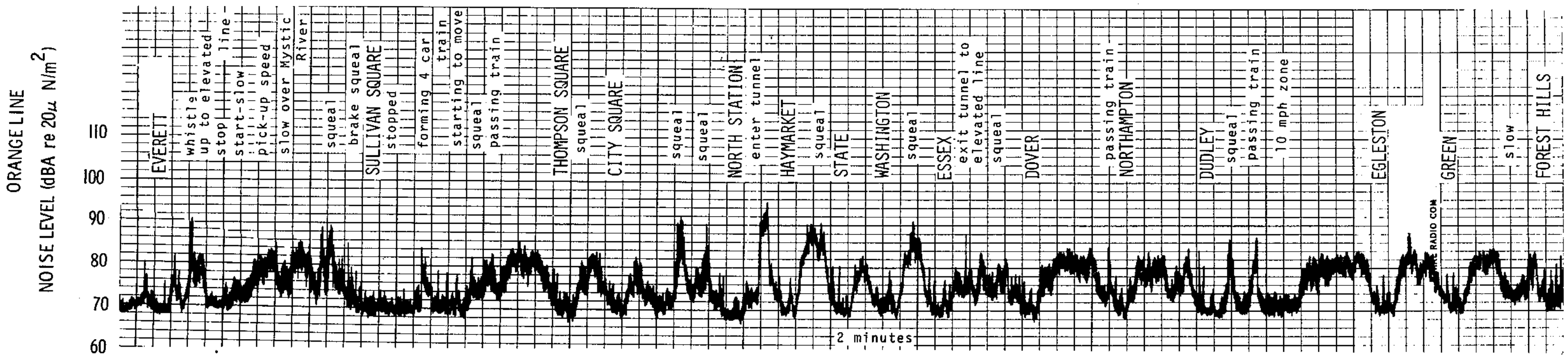


Figure A-1. In-Car Noise Level Time History - Blue Line, Car No. 0582, 10/27/72



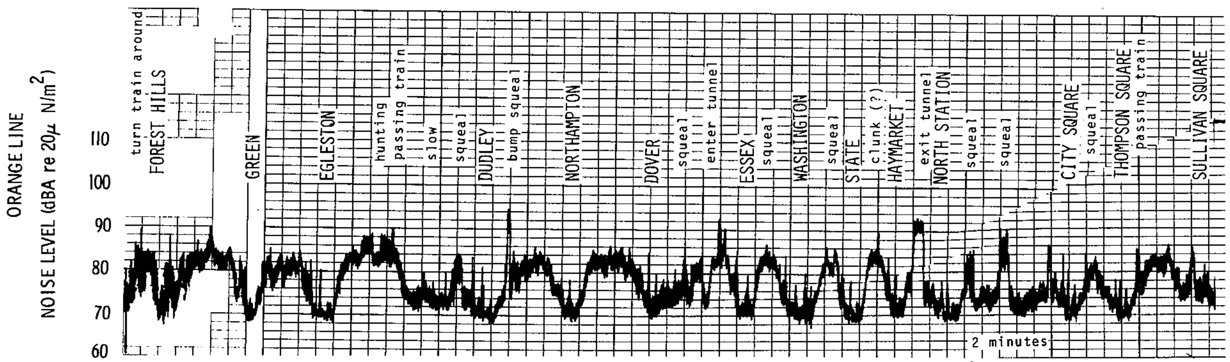
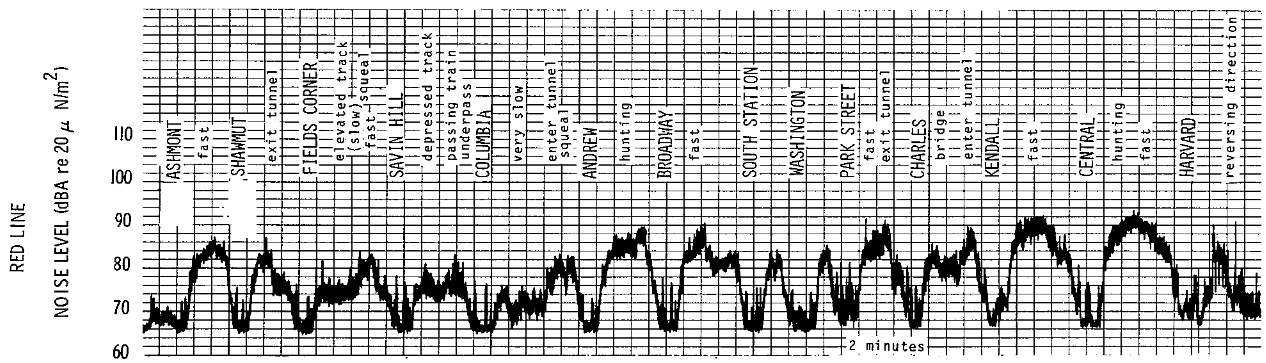


Figure A-2. In-Car Noise Level Time History - Orange Line, Car No. 01105



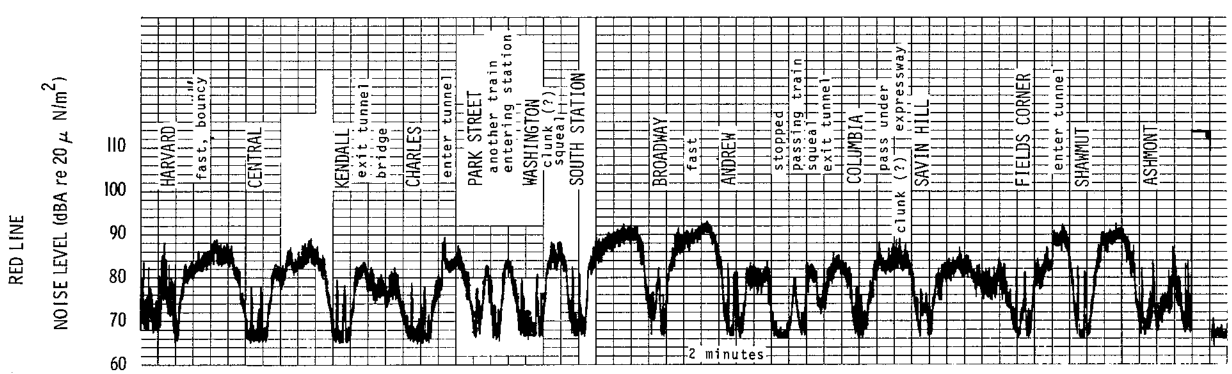


Figure A-3. In-Car Noise Level Time History - Red Line, Car No. 01480 (Bluebird)

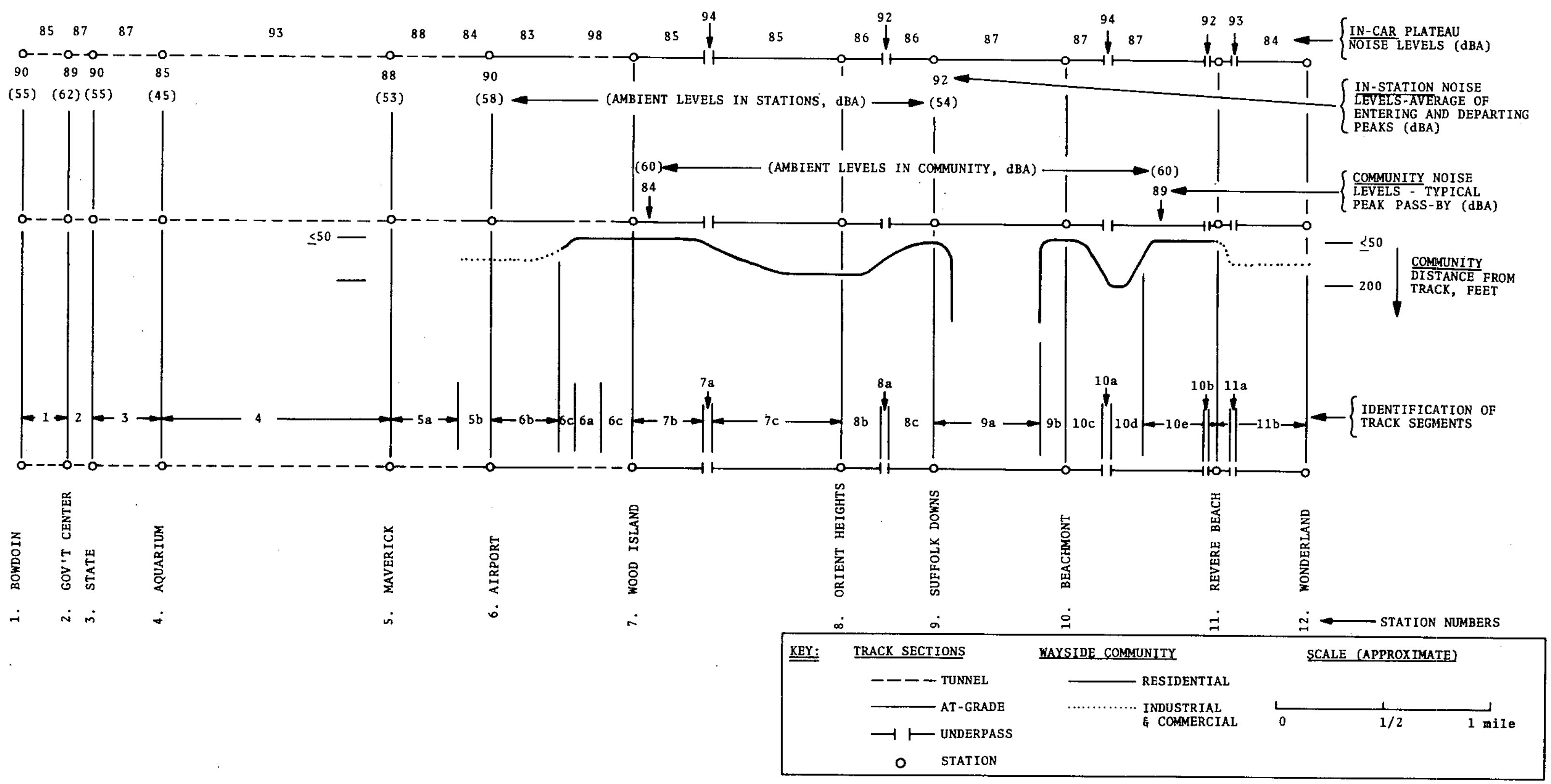


Figure A-4. MBTA Blue Line Noise Measurement Summary

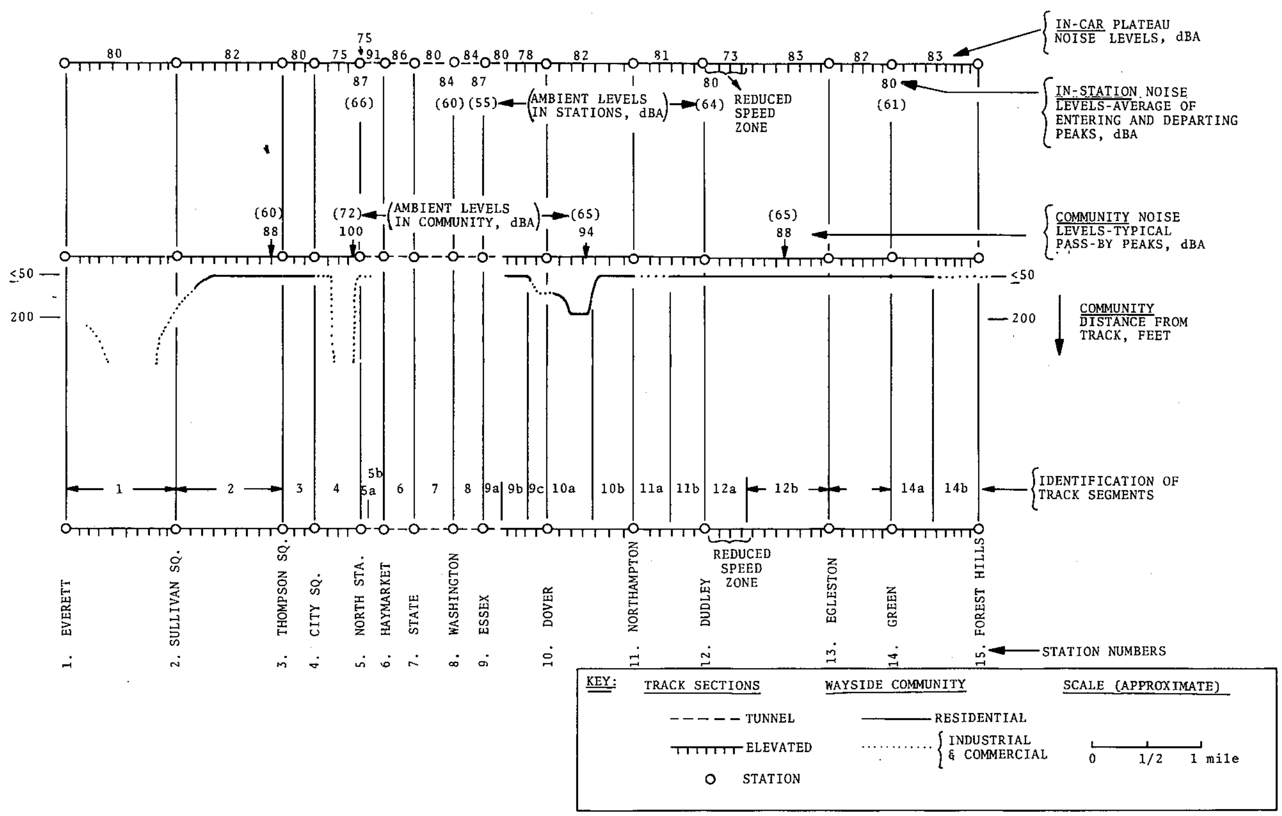


Figure A-5. MBTA Orange Line Noise Measurement Summary

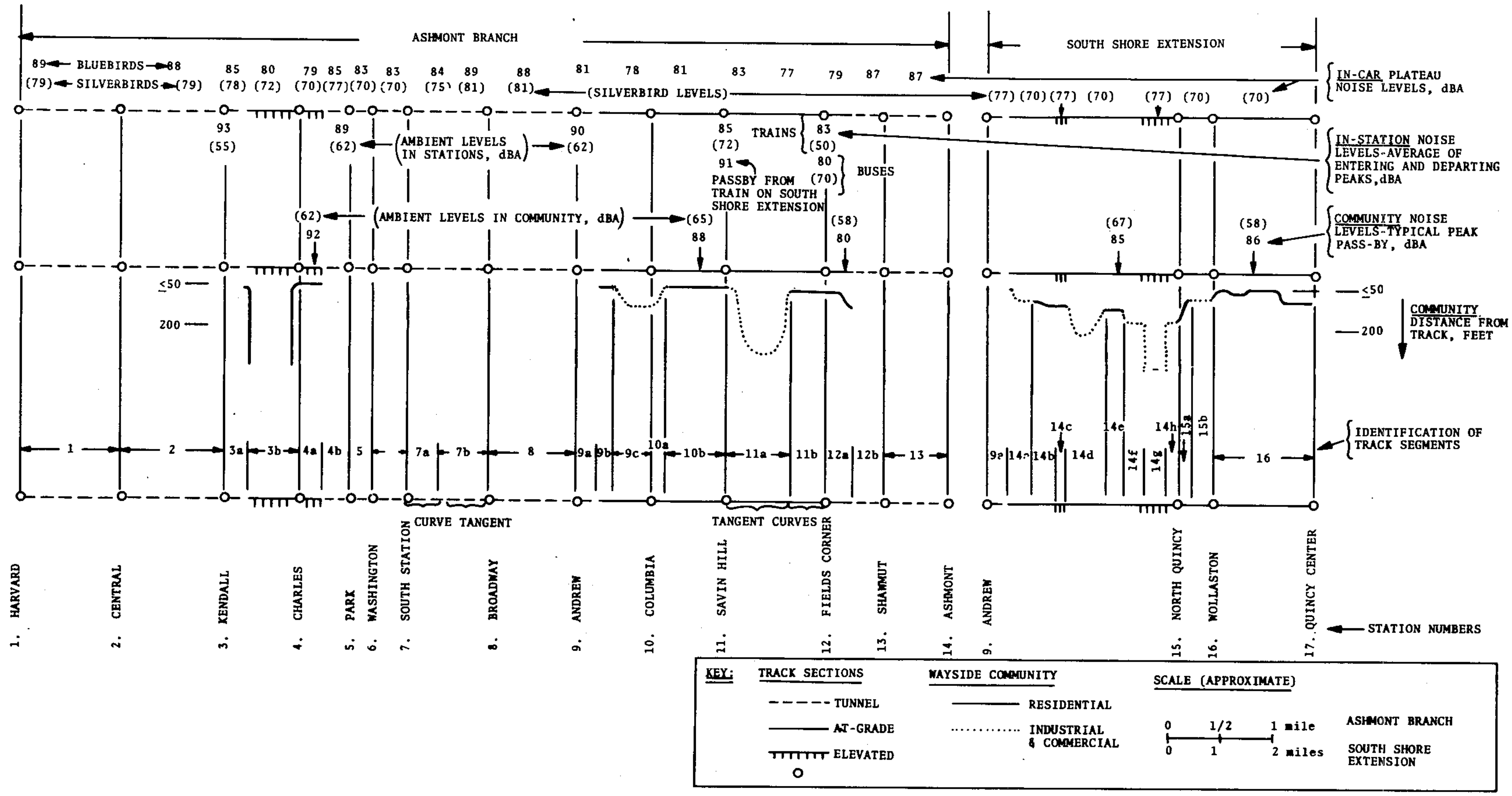


Figure A-6. MBTA Red Line Noise Measurement Summary

APPENDIX B

ALGORITHM FOR MINIMIZING NOISE CONTROL COSTS

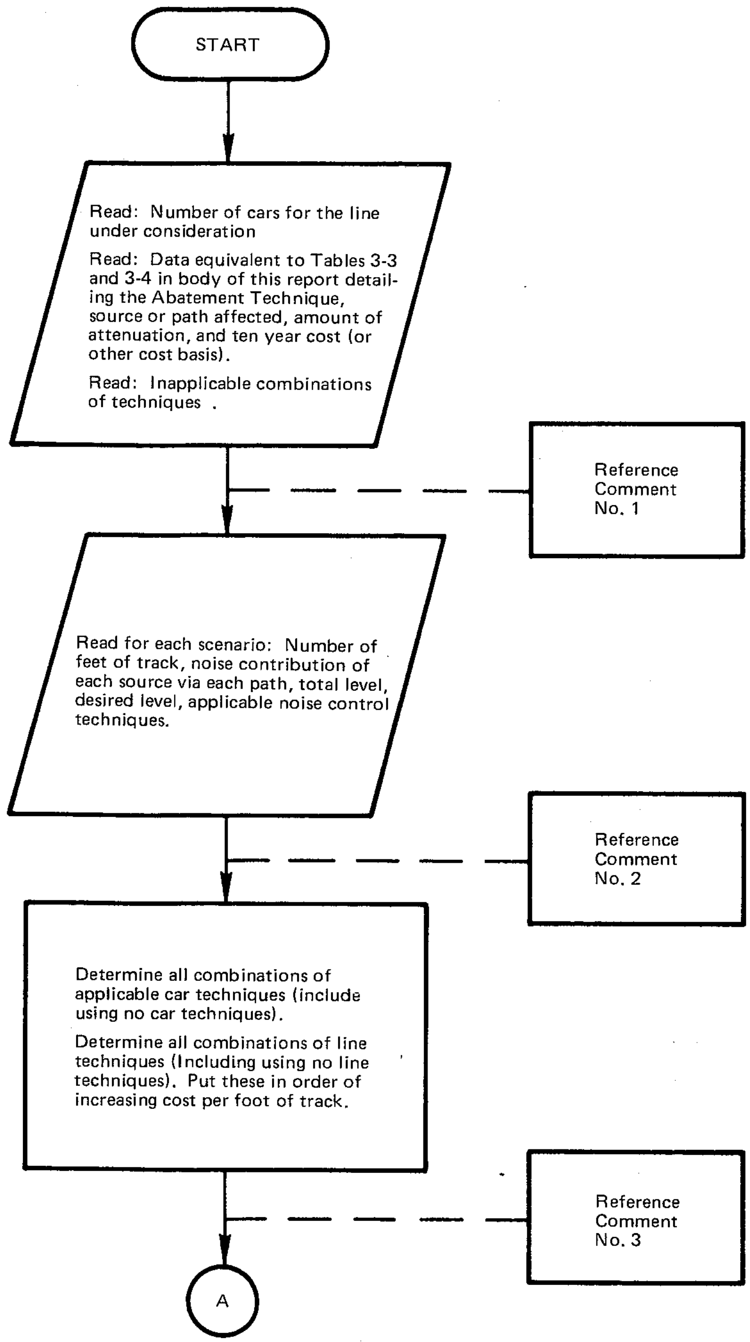
The algorithm for Cost-Abatement analysis presented here will determine how to achieve at least cost a desired set of noise levels along a rail transit line. The algorithm is given in the form of a simplified logic flow diagram, the main purpose of which is to convey to the reader the essential features of the computer program developed by TSC.

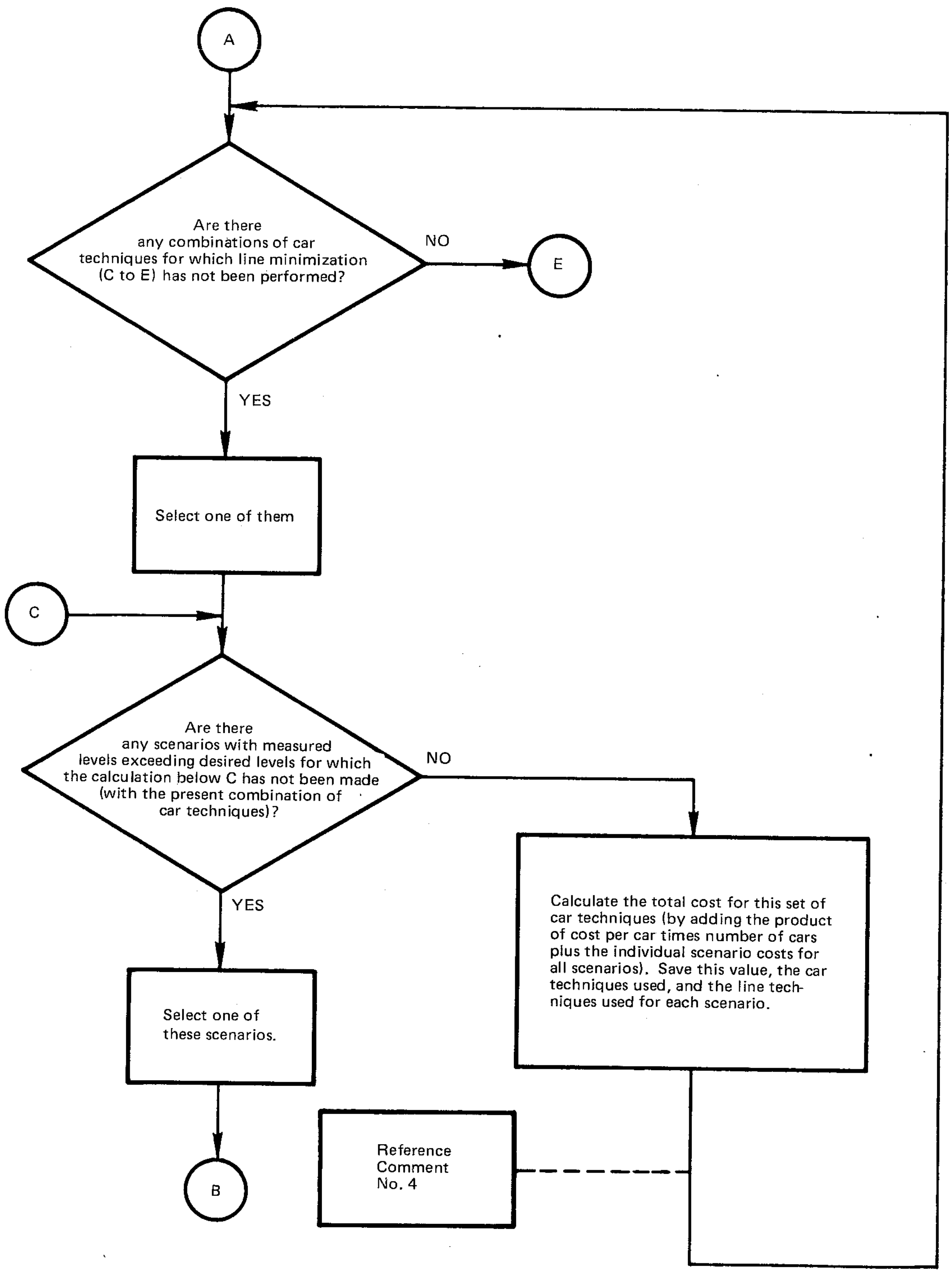
Although the program is designed specifically for rapid transit systems, the approach is generally applicable to minimize noise control costs on any vehicle-guideway transportation system. An equivalent but less formal procedure (using pencil, paper, and programmable desk calculator) was followed in the MBTA pilot study. There, all scenarios were assigned identical desired levels. The present algorithm, and its associated program permits each scenario to have a separately assigned desired level.

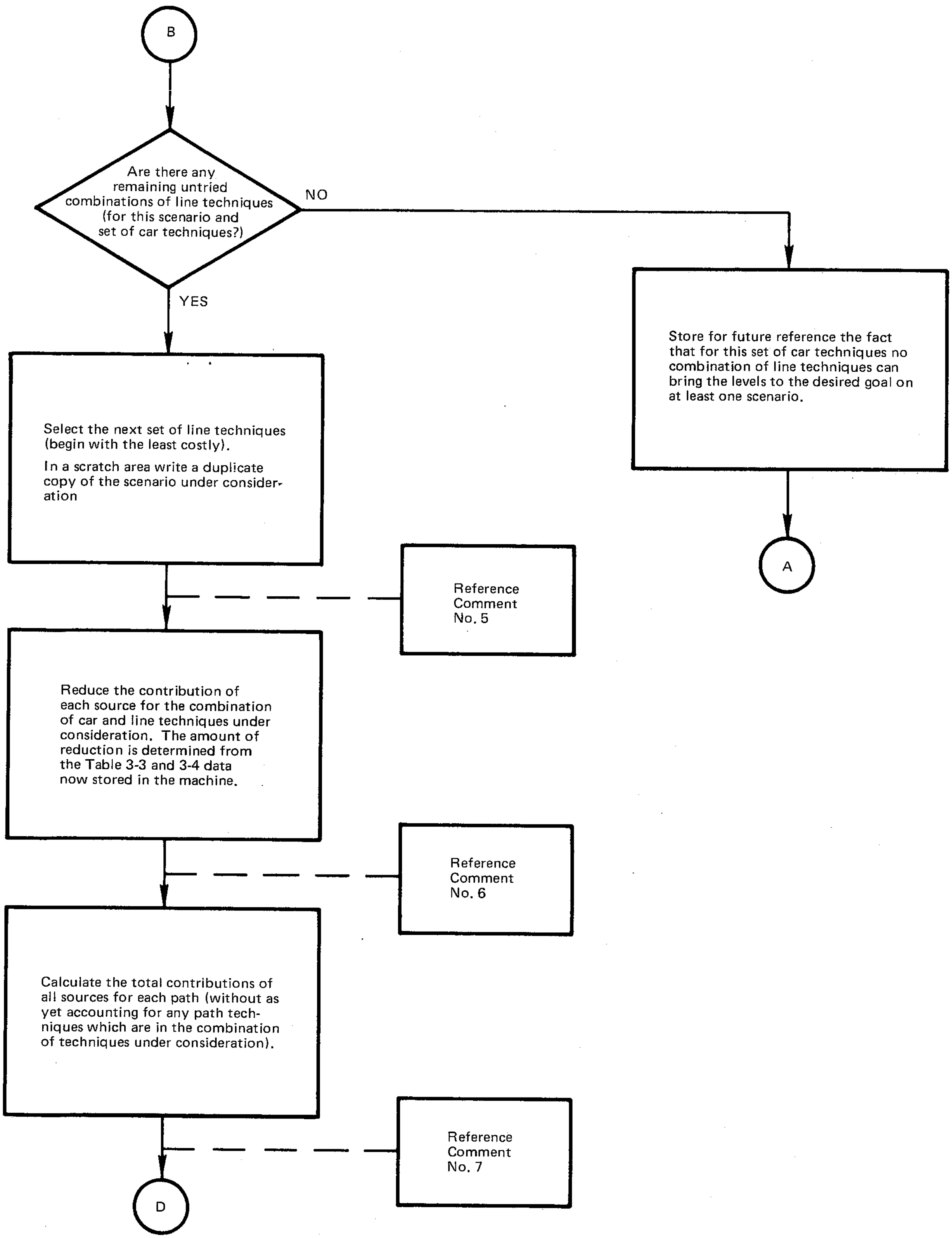
The algorithm depends fundamentally on the segmentation of the system into acoustically similar noise control groups, and on the noise scenarios determined for each group and given by the user as an input to the algorithm. It also depends on the compilation of cost and acoustic data for the noise control techniques available, such as is given in Tables 3-3 and 3-4.

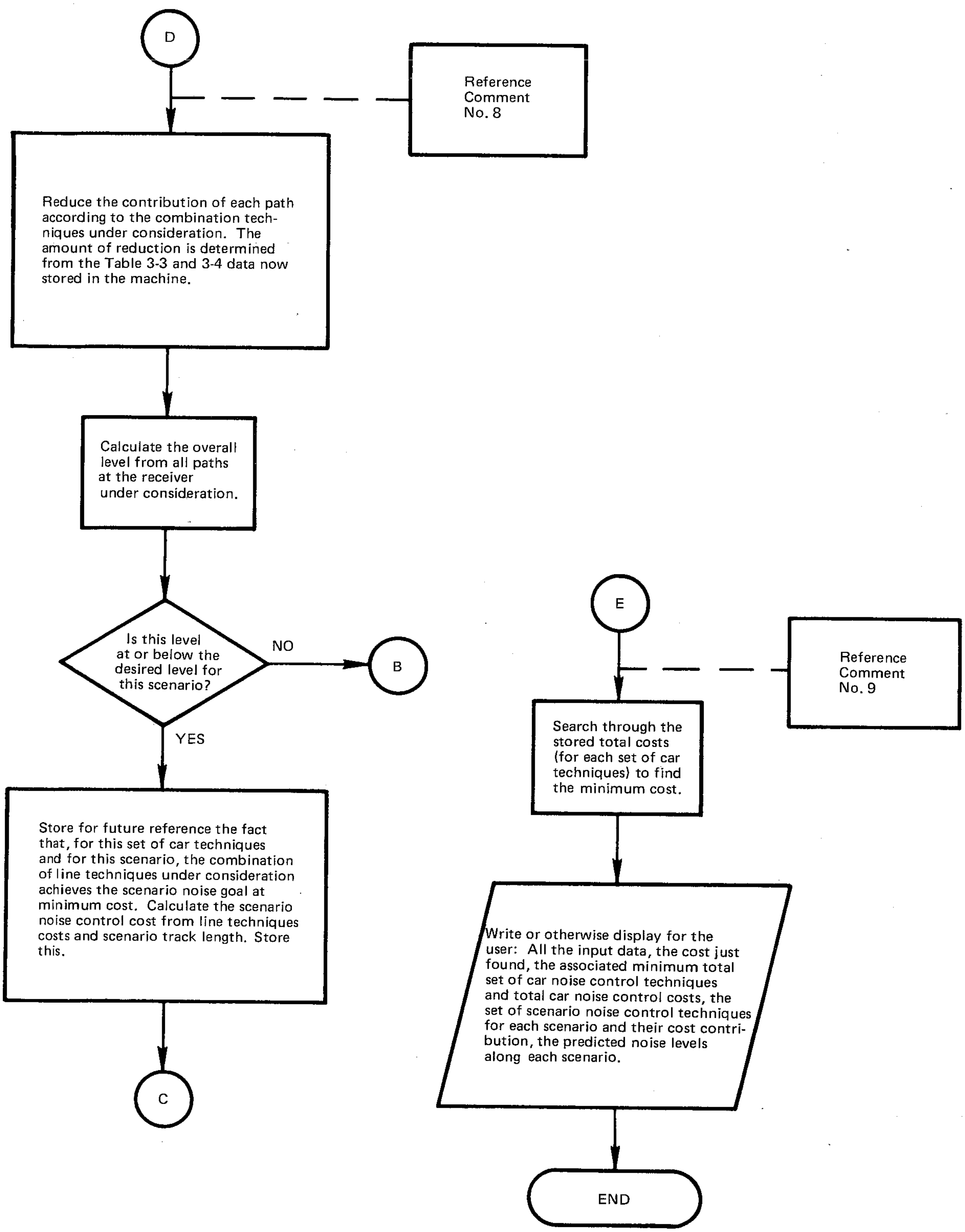
The logic presented here treats only one reciever type for each segment of track. That is, the algorithm solves the rider, station and community problems independently whereas, in general, these are coupled (see discussion in Section 3.3.2). A more advanced program is under development to handle the coupled problem. Discussion of its design and the appropriate expanded definition of a scenario for its application are beyond the scope of the present report.

The actual computer program follows the basic structure outlined below but also includes additional features to improve running time and user-oriented outputs. Embellishments not central to understanding the program, however, are not included in the logic outline.


START
Read: Number of cars for the line under consideration
Read: Data equivalent to Tables 3-3 and 3-4 in body of this report detailing the Abatement Technique, source or path affected, amount of attenuation, and ten year cost (or other cost basis).
Read: Inapplicable combinations of techniques .
Reference Comment No. 1
Read for each scenario: Number of feet of track, noise contribution of each source via each path, total level, desired level, applicable noise control techniques.
Reference Comment No. 2
Determine all combinations of applicable car techniques (include using no car techniques).
Determine all combinations of line techniques (Including using no line techniques). Put these in order of increasing cost per foot of track.
Reference Comment No. 3
A


A
Are there any combinations of car techniques for which line minimization (C to E) has not been performed?
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
YES
Calculate the total cost for this set of car techniques (by adding the product of cost per car times number of cars plus the individual scenario costs for all scenarios). Save this value, the car techniques used, and the line techniques used for each scenario.
Select one of these scenarios.
B
Reference Comment No. 4


B
Are there any remaining untried combinations of line techniques (for this scenario and set of car techniques?)
NO
YES
Store for future reference the fact that for this set of car techniques no combination of line techniques can bring the levels to the desired goal on at least one scenario.
A
Select the next set of line techniques (begin with the least costly).
In a scratch area write a duplicate copy of the scenario under consider-ation
Reference Comment No. 5
Reduce the contribution of each source for the combination of car and line techniques under consideration. The amount of reduction is determined from the Table 3-3 and 3-4 data now stored in the machine.
Reference Comment No. 6
Calculate the total contributions of all sources for each path (without as yet accounting for any path tech-niques which are in the combination of techniques under consideration).
Reference Comment No. 7
D


D
Reference Comment No. 8
Reduce the contribution of each path according to the combination techniques under consideration. The amount of reduction is determined from the Table 3-3 and 3-4 data now stored in the machine.
Calculate 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
Store for future reference the fact that, for this set of car techniques and for this scenario, the combination of line techniques under consideration achieves the scenario noise goal at minimum cost. Calculate the scenario noise control cost from line techniques costs and scenario track length. Store this.
C
E
Reference Comment No. 9
Search through the stored total costs (for each set of car techniques) to find the minimum cost.
Write or otherwise display for the user: All the input data, the cost just found, the associated minimum total set of car noise control techniques and total car noise control costs, the set of scenario noise control techniques for each scenario and their cost contribution, the predicted noise levels along each scenario.
END

Reference Comments:

1. Combinations involving both welded rail and epoxy joints for example would be inapplicable since they are mutually exclusive. Likewise for resilient and damped wheels.

2. User identifies techniques such as barriers, resilient wheels, welded rail, etc. for a community noise scenario. Techniques such as station acoustic treatment would be inapplicable there.

3. If there are S scenarios, L line noise reduction techniques and C car reduction techniques then there are $2^{(SL + C)}$ different possible combinations of techniques and locations along the line for applying them. For S=11, L=10 and C=9 this is 2^{119} or about 10^{36} combinations. The most straightforward way to proceed is simply to calculate the total cost and new scenario levels for each of these combinations over the whole line and save at any point in the calculation the cheapest (or several cheapest) combinations 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 $S \times 2^{L+C}$ or about 10^7 combinations in our present example. The number of calculations may be further reduced: (1) by starting with inexpensive combinations and working up (in cost) until the noise goals are satisfied as is done in this algorithm, and, (2) by eliminating inapplicable combinations ahead of time, (3) In actual application it is usually possible to eliminate other combinations which are in the strictest sense applicable but which only attenuate sources or paths known by the user to be already well below the scenario goal.

4. We now have the minimum cost for the particular set of car techniques just considered, and the line techniques which achieve it.

5. First apply techniques (both car and line) which reduce the source levels.

6. Where sources transmit via several paths, reduce their contribution via each path by the same amount.

7. Convert from dB to linear quantities before addition or use so-called "logarithmic addition" discussed in Section 3.2.4, Fig. 3.2.

8. Next account for the path attenuation techniques (both car and line).

9. We now have the minimum total cost (for car plus line) for each combination of car techniques. The least possible cost, which we seek, is the minimum of these minima.

APPENDIX C

GLOSSARY

GLOSSARY
(DEFINITIONS AS USED IN THIS REPORT)

Ambient Noise - The all-encompassing noise associated with a given environment, excluding the noise event(s) under specific study.

Average Maximum Station Noise Level - The arithmetic average of two maximum A-weighted sound pressure levels, one for the train entering and one for it departing a station.

Impact (noise) - Acoustic noise, generated during rolling contact, resulting from a geometric discontinuity of the rolling surfaces (e.g., wheel flats, rail joints).

Maximum Pass-by Noise Level - The maximum value (as measured with a slow meter response) of the A-weighted sound pressure level during a train pass-by. (See, for example, Figure 2.3)

Noise Level - The A-weighted sound pressure level.

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

Plateau Noise Level - The average in-car noise level while traveling at constant speed between stations. (See, for example, Figure 2.1.)

Roar (noise) - The noise, due to rolling contact, that is not accounted for by impact and wheel squeal. For example, the wheel/rail noise resulting from constant speed operation on non-flat wheels and continuous welded tangent track.

Scenario (noise control) - The formalized listing of the contributions to the overall noise level at a specific receiver location made by each major noise source via each major noise path.

Singularities (noise) - Those noise sources not taken into account by the chosen methods for describing the in-car, station, and community noise, i.e., those sources not included in the scenarios. These singularities include, wheel squeal, noisy door operation, brake squeal and vehicle hunting.

Wheel Squeal - A tonal or nearly tonal noise (sometimes several frequencies simultaneously) that is usually associated with curve negotiation, although it sometimes occurs during braking, acceleration, and even occassionally during steady tangent track operation.

APPENDIX D

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REFERENCES

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