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 Abate-
ment. 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 proper-
ties. A methodology is described for assessing the noise climate and for select-
ing 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:

o   Estimates of capital and maintenance costs for applying proposed noise control standards to operating properties.

o   Site specific noise abatement requirements for existing U.S. urban rail transit properties.

o   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

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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:
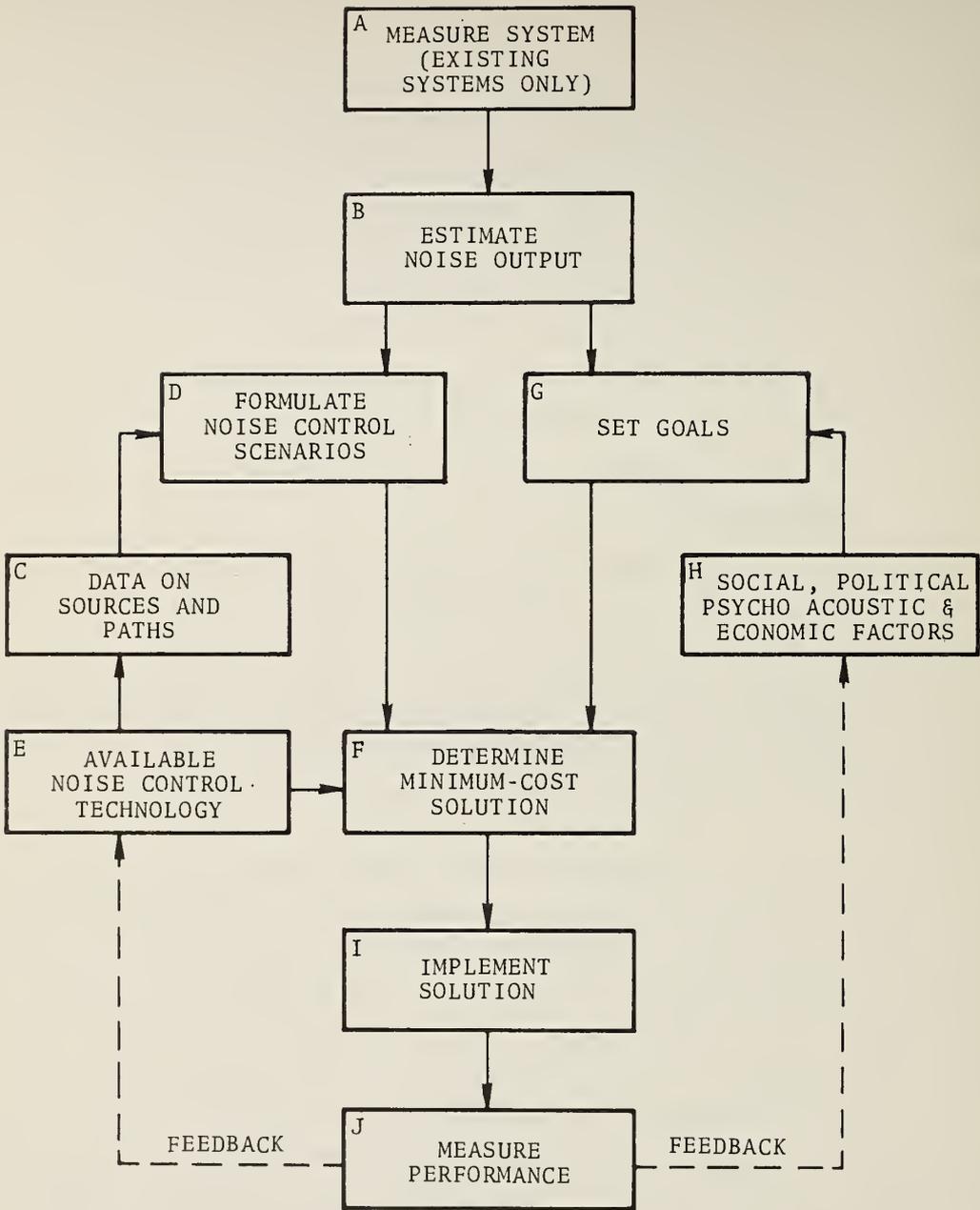
Figure 1-1 Rapid Rail Transit Noise Control Schematic

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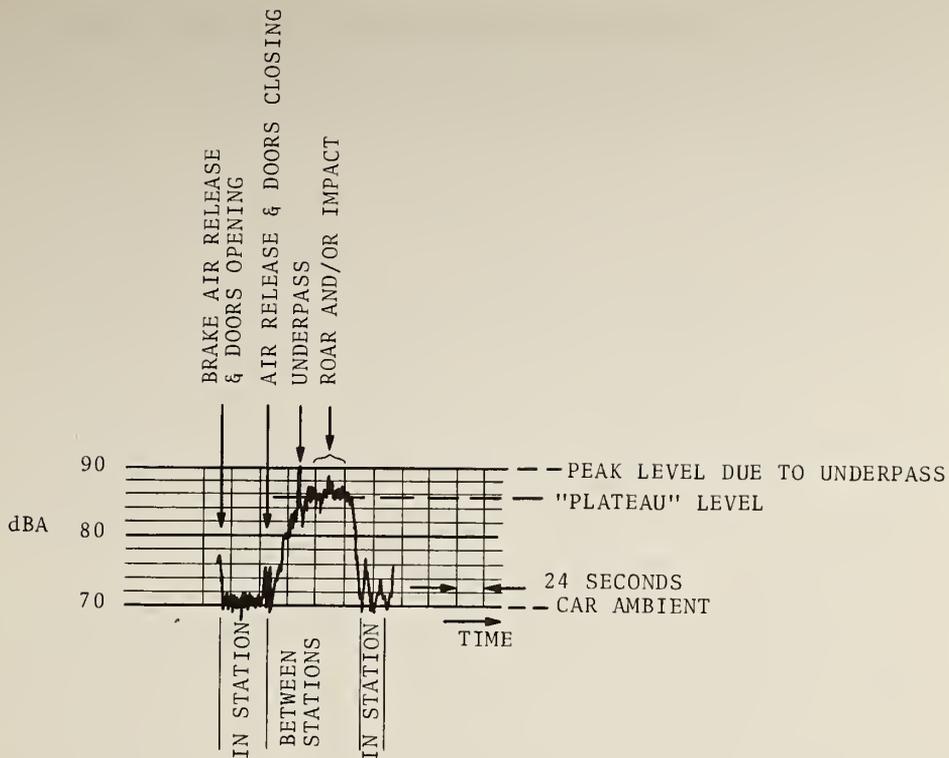
Figure 2-1   Sample Time History of In-Car Noise Levels (dBA)

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 notice-able 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 plat-
form 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 pro-
pulsion 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-gene-
rators, 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.
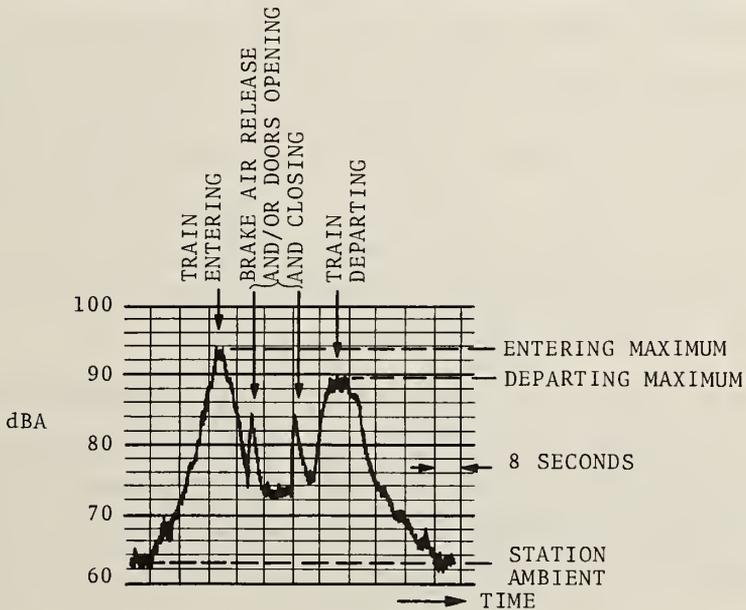
Figure 2-2   Sample Time History of Station Platform
Noise Levels (dBA)

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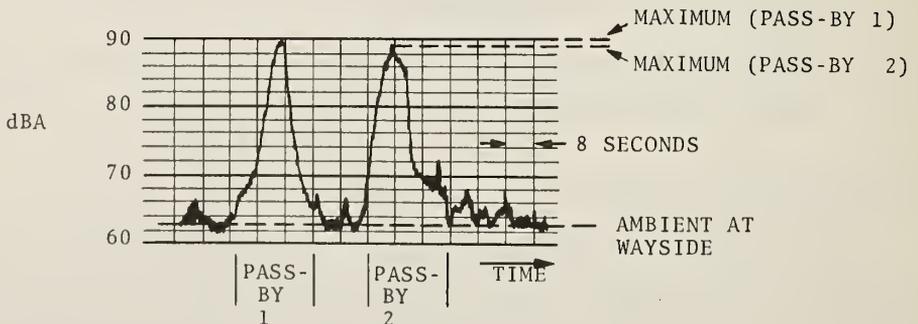
Figure 2-3.   Sample Time History of Wayside Noise Levels (dBA) for Two 4-Car Train Pass-Bys in Succession

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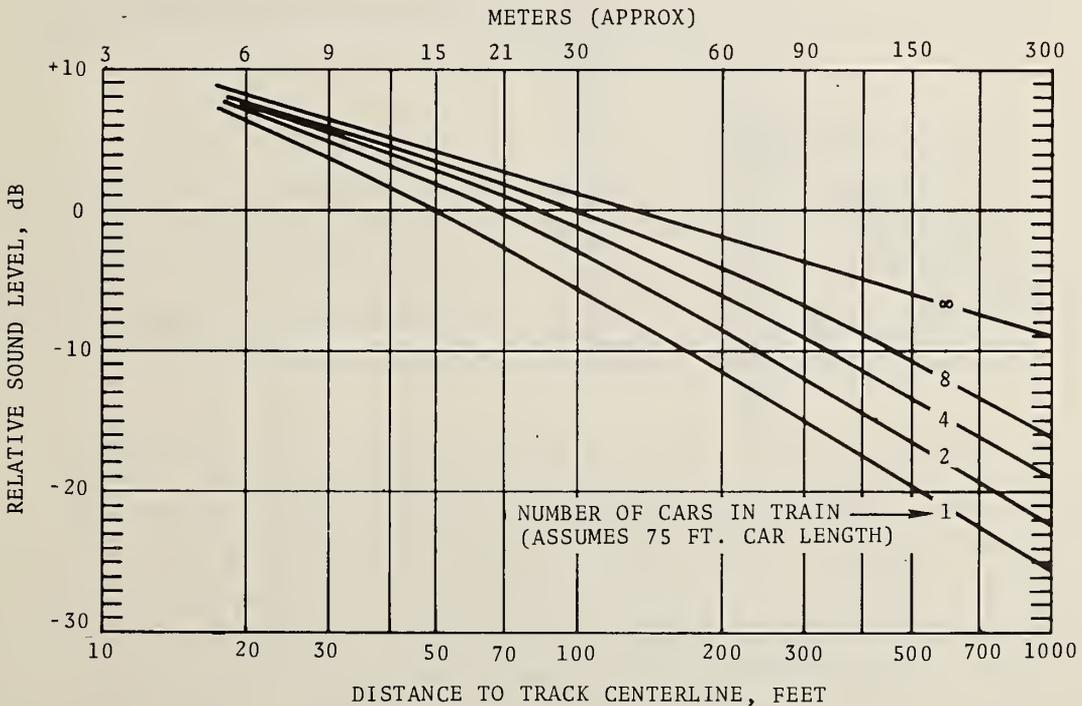
Figure 2-4.   Change in Sound Level with Distance from the Track
Relative to a One Car Train at 50 Feet

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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 apply-
ing 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 Wonder-
land 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.

RAPID TRANSIT LINES

ORANGE LINE
- EVERETT
- SULLIVAN SQUARE
- THOMPSON SQUARE
- CITY SQUARE
- NORTH STATION
- HAYMARKET

BLUE LINE
- WONDERLAND
- REVERE BEACH
- BEACHMONT
- SUFFOLK DOWNS
- ORIENT HEIGHTS
- WOOD ISLAND
- AIRPORT
- MAVERICK
- AQUARIUM

BOWDOIN
GOVERMENT CTR   STATE

RED LINE
HARVARD   CENTRAL   KENDALL   CHARLES   PARK STREET

WASHINGTON
- SOUTH STATION
- ESSEX
- BROADWAY
- DOVER
- ANDREW
- NORTHAMPTON
- NORTH QUINCY
- DUDLEY
- WOLLASTON
- COLUMBIA
- EGLESTON
- QUINCY CENTER
- SAVIN HILL
- SOUTH SHORE EXTENTION
- GREEN
- FIELDS CORNER
- FOREST HILLS
- SHAWMUT
- ASHMONT

Figure 2-5.   MBTA Rapid Transit Lines - Schematic

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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 in-cluded 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	RI	2,770	5	R2	2,460	1,2,3	R3
UNDERPASS	180	7a,10a 11a	RI	120	8a,10b	R2	-	-	-
AT-GRADE	-	-	-	-	-	-	17,550	6b,6c,7b, 7c,8b,8c 9a,9b, 10c,10d 10e, 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	RII	-	-	
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.
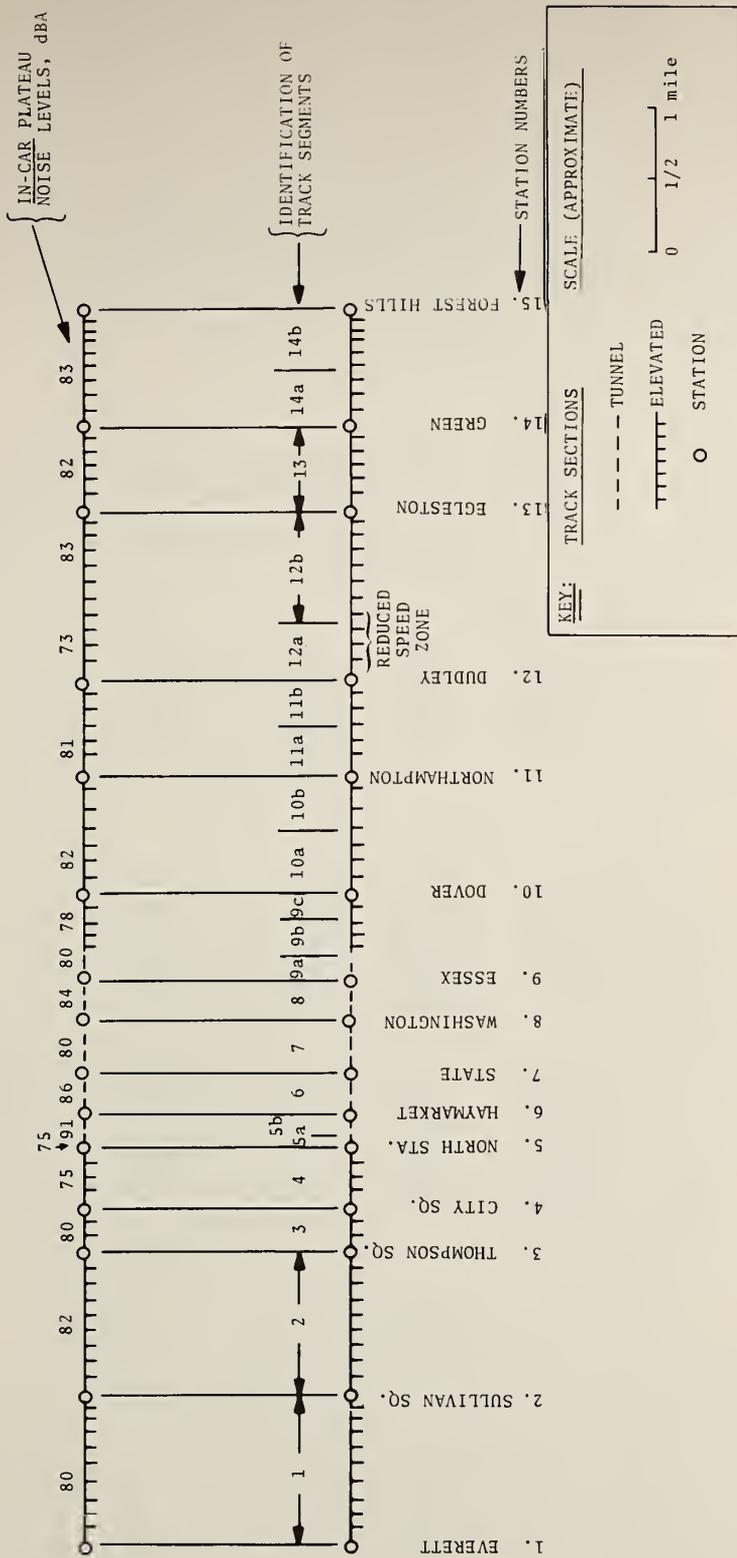
Figure 2-6. In-Car Plateau Noise Levels for the MBTA Orange Line

2-19

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 sur- face 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 sur- face 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 sur- face 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 sur- face 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 sur- face 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

2-22
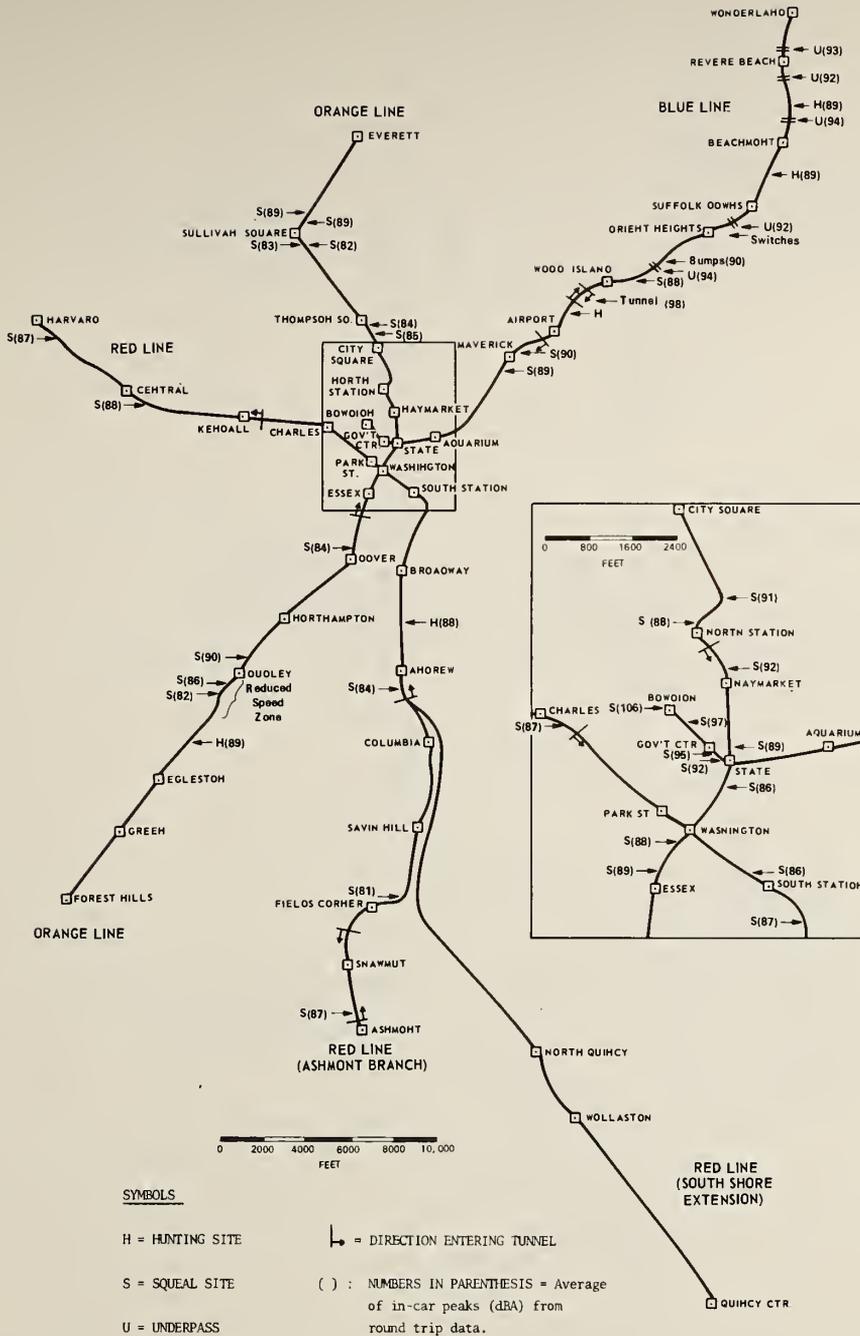
Figure 2-7. Site Specific In-Car Noise Problems
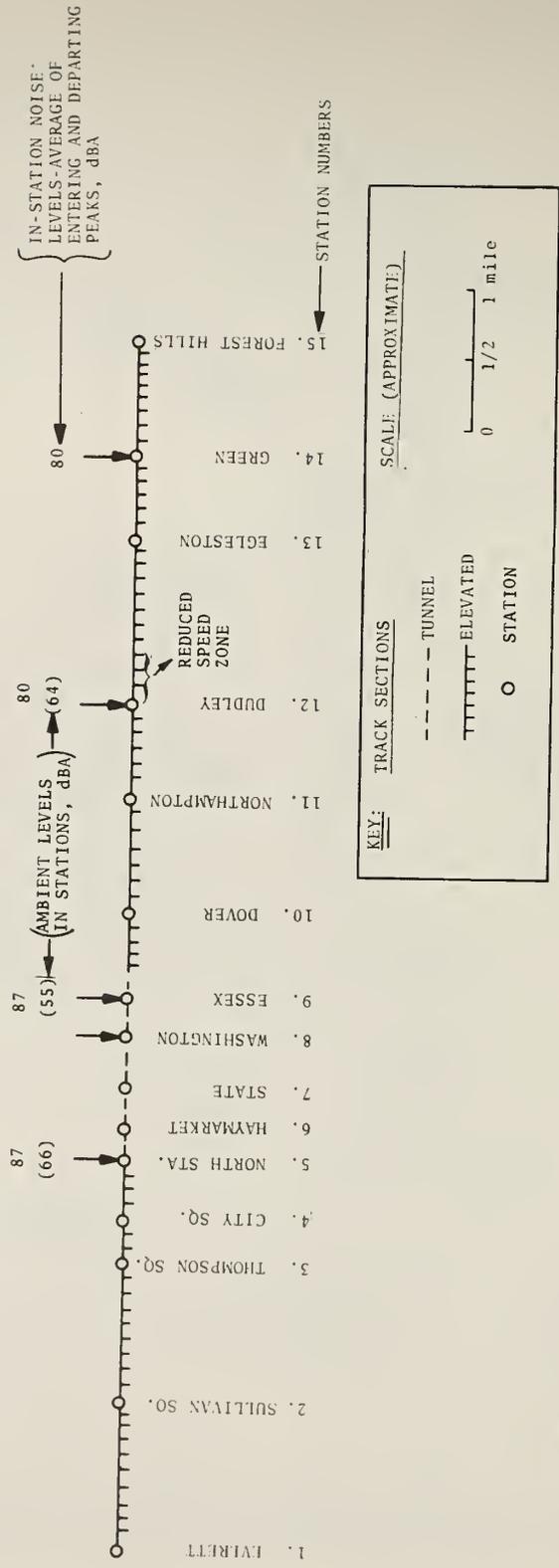
Figure 2-8. Average Maximum Station Platform Noise Levels for the MBTA Orange Line
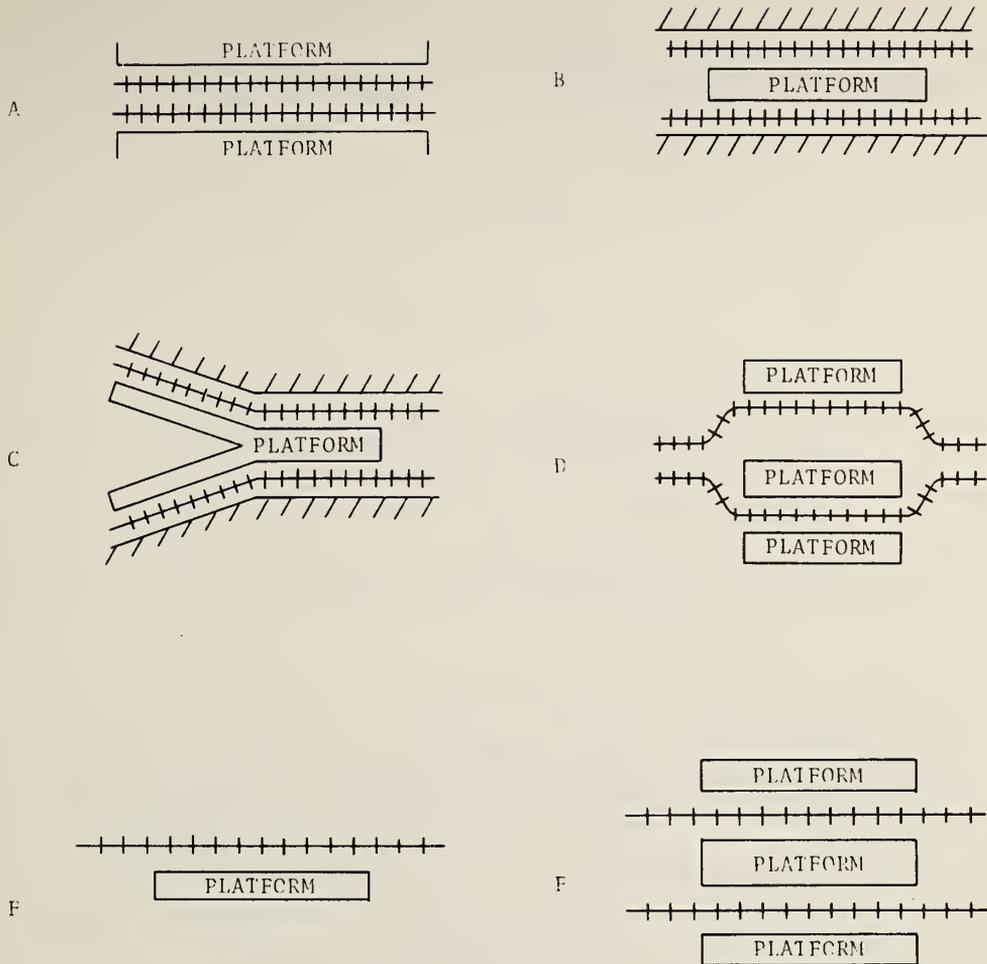
Figure 2-9. Track Configurations at Stations

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 considera-
tion 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 dis-
tance to the nearest wayside structure (Section 2.2.3, step (2)).
Isolated structures deviating from the general pattern of a com-
munity 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 Appen-
dix A.

Estimated wayside levels were determined for each segment
not having an actual measurement by extrapolating from the measure-
ments of an acoustically similar segment. Spreading was calculated
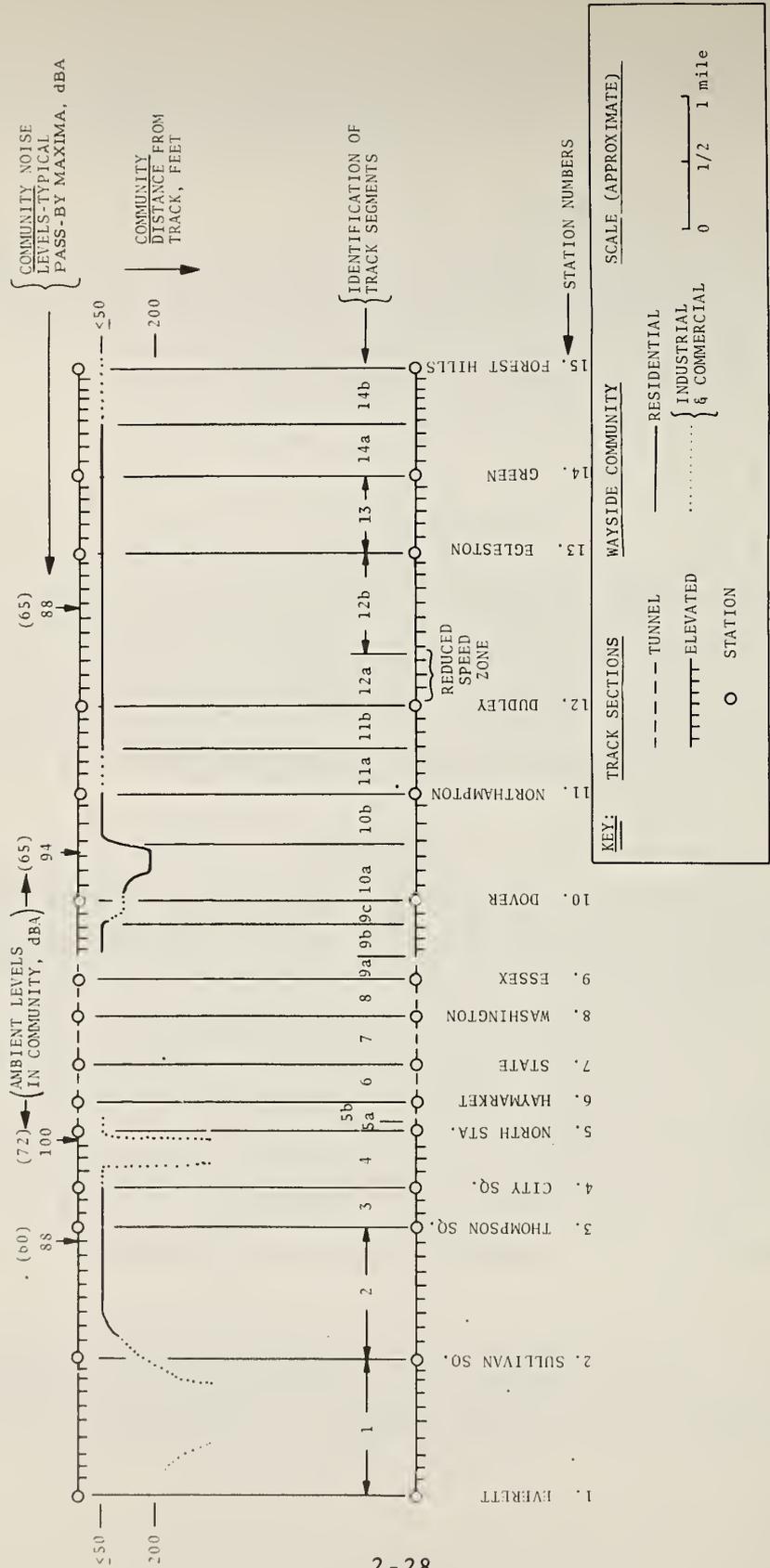
Figure 2-10. Typical Distance to Wayside Community and Average Maximum Pass-by Levels along the MBTA Orange Line

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.
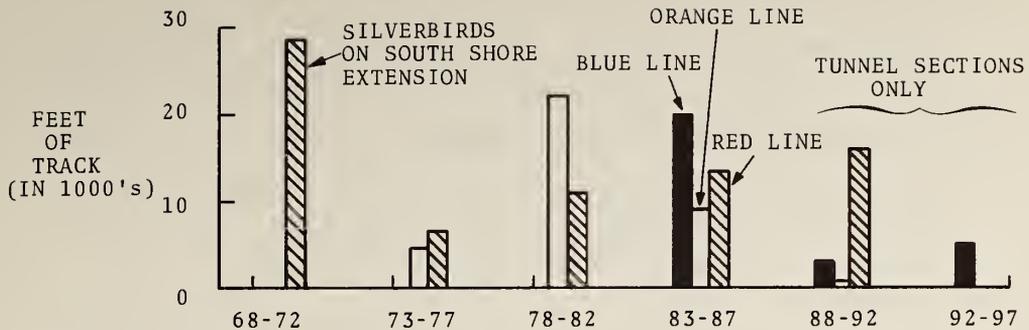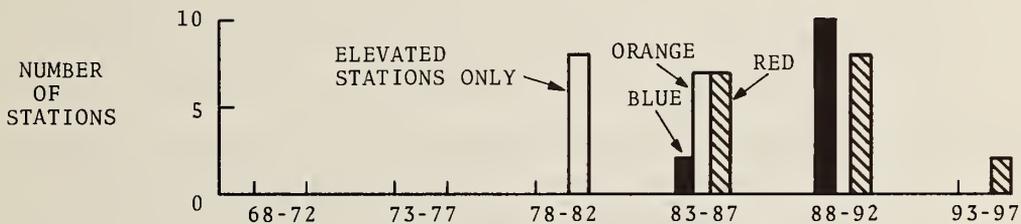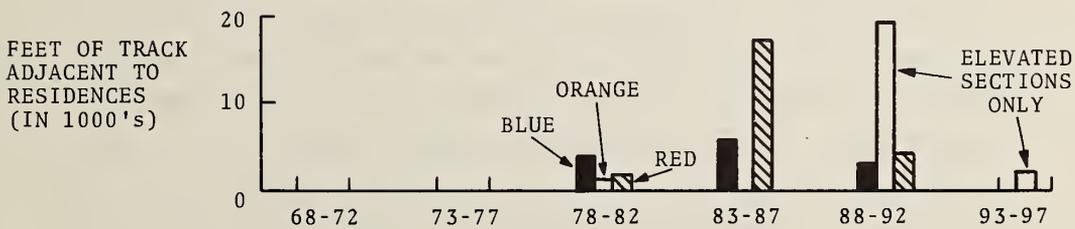
Figure 2-11. Summary of MBTA Noise Status

2-31

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 over-all 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 over-all 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, esti-mate 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 con-trol technology. For each abatement technique, deter-mine which noise sources or paths are affected, the poten-tial 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

TYPICAL SOURCES
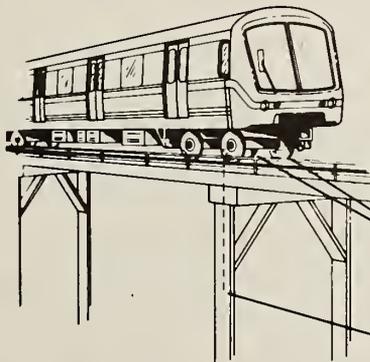
RAIL JOINTS ("IMPACT")
MICROROUGHNESS ("ROAR")
POWER PICKUP
PROPULSION
AUXILIARIES

TYPICAL PATHS
TO COMMUNITY

PATH 1:   DIRECT
          AIRBORNE

PATH 2:   STRUCTUREBORNE
          SECONDARY
          RADIATION

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 respectively.) 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 wayside 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 decrease 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 vibrating 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. It does not include noise contributions from singularities. 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 CONTRI- BUTION	SOURCE CONTRIBUTION (dBA)					
		RAIL JOINTS	RAIL ROUGH	WHEEL ROUGH	POWER PICKUP	PROPUL- SION	AUX
DIRECT AIRBORNE FROM UNDER CAR TO COMMUNITY (PATH 1)	84	82	76	76	60	69	60
STRUCTURE BORNE 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 SEG- MENTS 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 measure- ment 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

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 way-side 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

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 × 1 joint/39 ft × 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

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 soil-borne 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 non-combustible
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) 1. 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) } b. $64/ft. (8' high, 2 walls) } $4/ft^2 c. $16/ft (4' high, 2 platforms } 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

$$L_{comb} - L_1, \text{ dBA}$$

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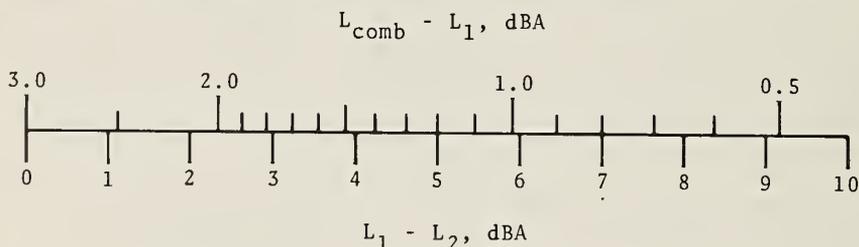
Note: $L_1 > L_2$, $L_{comb} = (L_{comb} - L_1) + L_1$

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)	Trans- mission Path	II Attenuated Path Contri- bution	III Unatten- uated Path Contri- bution	Source Contribution (dBA)					
						Rail Joints	Rail Rough- ness	Wheel Rough- ness	Power Pickup	Propul- sion	Auxil- iary
Scenario C-5	0	90	(1) Air- borne	84	84	82	76	76	60	69	60
			(2) Struc- tureborne	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 atten-
       uated by an estimated 10 dBA. Overall noise level is re-
       duced 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	RESILIENT FASTENER	40
	C4, C5	TRACK ADJUSTMENTS DAMPED WHEELS	
85	C4	WELDED RAIL	240
	C4, C5	TRACK ADJUSTMENTS DAMPED WHEELS RESILIENT FASTENERS	
80	C4	GROUND RAIL TRUED WHEELS	750
	C4, C5	TRACK ADJUSTMENTS DAMPED WHEELS RESILIENT FASTENERS WELDED RAIL	
75	C4	BARRIER (NON-ABSORPTIVE)	1410
	C4, C5	TRACK ADJUSTMENTS DAMPED WHEELS RESILIENT FASTENERS GROUND RAIL TRUED WHEELS WELDED RAIL	

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 iden-
tified 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 per-
formed 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 con-
struction 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*	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   Where
P4 = Pg+Pd+Pb
P5 = Pf

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)

Scenario	Total Plateau Level (dBA)	Path Contri- bution	Path*	Scenarios for In-Car Noise Levels Source Noise Levels (dBA)								Line Element
				Wheel Flats	Rail Joints	Rail Rough- ness	Wheel Rough- ness	Power Pickup	Propul- sion	Aux. (Mech)	Aux. (Aero)	
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   } Where

P4 = Pg+Pd+Pb

P5 = Pf

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 (3 of 3)

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
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	

Scenarios for In-Car Noise Levels
Source Noise Levels (dBA)

* Path Definitions

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

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

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.	PATH	SOURCE NOISE LEVELS (dBA)								CONSTRUCTION
				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 abate-
ment techniques have only an initial installation cost, some have
only maintenance type costs, and other have both initial and main-
tenance 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

LINE TREATMENT	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 tech-
niques 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 con-
sidering 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:

| RECEIVER | RIDER | | | |
DESIRED LEVEL (dBA)	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	Weld Rail		
	R1, R2, R3, R5	Seal Car, Interior Car Absorption	274	1.3
75	R1, R2, R5	Weld Rail		
	R1	Grind Rail	970	2.8
	R1	True Wheels		
	R3	Improve Joints		
	R1, R2, R3, R5	Seal Car, Interior Car Absorption		

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.

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

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.

RECEIVER	COMMUNITY			
DESIRED LEVEL (dBA)	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		
	C1, C2	Barrier (Non-absorptive)	757	6.6
	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)	NORMAL-IZED COST (c) COST UNITS/dBA-FT.
90	-	-	NONE	-
85	R2	Weld Rail Grind Rail	9	9.5
80	R2	Weld Rail	149	3.2
	R7	Improve Joints		
	R2, R3, R7	Seal Cars		
75	R2, R7	Weld Rail	424	2.1
	R3 R2, R3, R4, R7, R8	Improve Joints Seal Cars Interior Car Absorption		

FOOTNOTES:

(a) The base costs, for elimination of noise singularities are not in-cluded in this table. These costs are identified in Table 3-11. Refer to Tables 2-1, 2-3 and 2-4 for identification of the track seg-ments and stations covered by each scenario. Scenario numbers are identical with the corresponding noise control group numbers.

(b)

(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 Plat- form Treatment True Wheels	636	11.6

FOOTNOTES: (a) The base costs, for elimination of noise singularities are not in-cluded 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 seg-ments 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)	NORMAL-IZED COST (c) COST UNITS/dBA-FT.
90	C4	Resilient Rail Fasteners	14	1.5
85	C4	Weld Rail	212	1.9
	C4,C5	Resilient Rail FASTENERS		
80	C4,C5	Weld Rail Resilient Rail Fasteners	725	3.3
	C4	Grind Rails, True Wheels		
75	C4	Barrier (Non-Absorptive	1386	4.2
	C4,C5	Weld Rail, Grind Rail, True Wheels		
	C4,C5, C6	Resilient Rail Fasteners		

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.

RECEIVER	RIDER			
DESIRED LEVEL (dBA)	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	Weld Rail	801	1.9
	R3, R6	Improve Joints		
	R9	True Wheels		
	R2, R3) R4, R5 (R6, R8)	Seal Cars, Interior Car Absorption		

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.

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	20	6.8
		Resilient Fasteners		
85	S1, S2; S3	Weld Rail	127	6.6
		Resilient Fastener		
	S1	Barrier		
80	S1, S2 ·S3, S9	Weld Rail	443	8.9
	S1, S2, S3	Resilient Fastener		
	S1, S2, S9	Barrier		
	S7, S8	Grind Rails		
	S1, S2, S3	Under Platform Treatment True Wheels		
75	S1, S2 S3, S9	Weld Rail	997	12.5
		Resilient Fastener		
	S1, S2, S9	Barrier		
	S3, S7, S8	Grind Rails		
	S1, S2, S3 S7, S8, S9	Under Platform Treatment		
	S1, S2	Wall Treatment		
	S1	Ceiling Treatment		
		True Wheels		

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.

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	94	4.6
	C5	Resilient Rail Fasteners		
80	C1	Barriers (Non-Absorptive)	448	2.7
	C2, C5	Weld Rail		
	C5	Resilient Rail Fasteners		
	C7, C8	True Wheels (Silver Birds Only)		
75	C1	Improve Joints	1851	5.7
	C3, C5	Weld Rail		
	C8	Grind Rail, True Wheels (Silver Birds Only)		
	C5	Resilient Rail Fasteners		
	C1, C2 C5, C7 C8	Barriers (Non-Absorptive)		

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		R2, C4	Weld Rail		R2	Seal Cars	-
	C1, S2, S3, S4 S2, S3 S2, S3	Weld Rail Resilient Fasteners Under Plat- form Treat.	358	R2	Grind Rail	221	C1, S1, S2, S3 C5, S1, S2, S3	Weld Rail Resilient Fasteners	313
				C4, C5	Resilient Fasteners		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.

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)
80	R1, C2, S2, S3, S4, S6, S7	Weld Rail		R2, C4, C5, S9, S10, S11	Weld Rail		R2, R3, R5	Seal Cars Interior Car Absorption	
	R1, R2 R3, R5	Seal Cars, Interior Car Absorption	984	R7	Improve Joints	1080	C2, C5, S1, S2, S3, S9	Weld Rail	999
	. 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	Blue			Orange			Red		
Desired Level (dBA)	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)	Scenario (b)	Abatement Techniques	Total Cost (a) (Cost Units)	Scenarios (b)	Abatement Techniques	Total Cost (a) (Cost Units)
75	R1, R2, R5, C2, S3, S4, S6, S7	Weld Rail		R2, R7, C4, C5, S5, S9, S10, S11, S12, S13, S14	Weld Rail		R2, R5, C3, C5, S1, S2, S3, S9	Weld Rail	
	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	2166	C8, S3, S7, S8	Grind Rails	3479
	C1, C2, S2, S4, S6	Barriers	2203	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.

3-41

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.

LINE \ RECEIVER	RIDER	STATION	COMMUNITY
BLUE	●	○	◊
ORANGE	▲	△	⬩
RED	■	□	⸬

NORMALIZED COST, COST UNITS/dBA-FT

— STATION AVERAGE

— COMMUNITY AVERAGE

— RIDER AVERAGE

20
10
5
3
2
1

90   85   80   75

MAXIMUM DESIRED SOUND PRESSURE LEVEL (dBA)
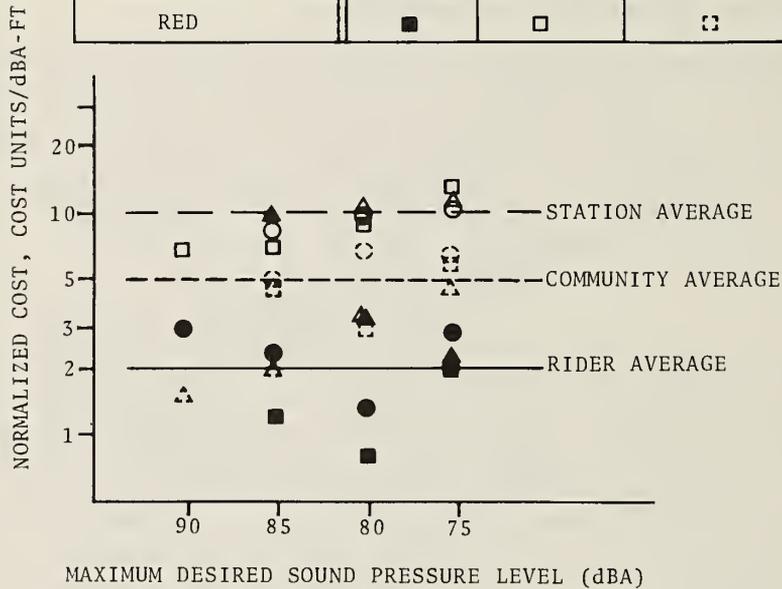
NOTE: THE NORMALIZED COST DOES NOT INCLUDE
        THE BASE COSTS IDENTIFIED IN TABLE 3-11.

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

A-2
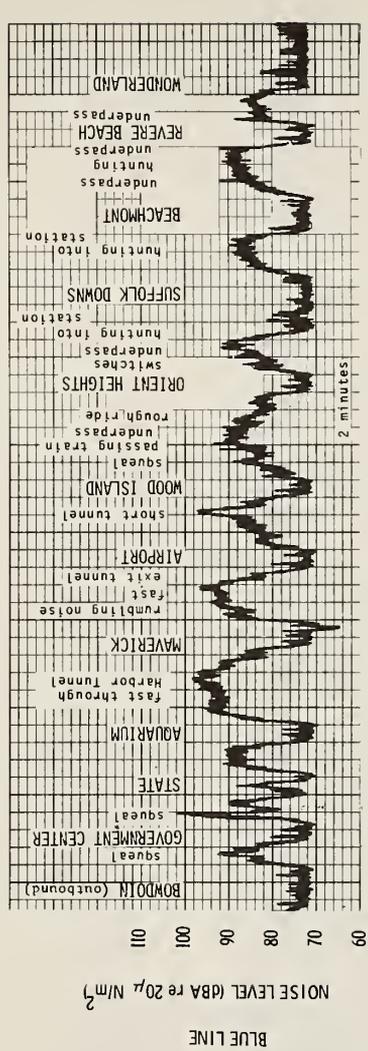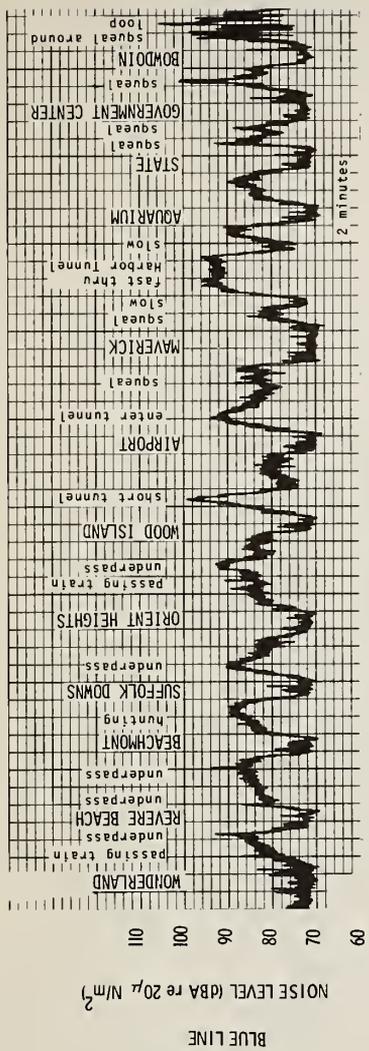
Figure A-1. In-Car Noise Level Time History - Blue Line, Car No. 0582, 10/27/72

A-3
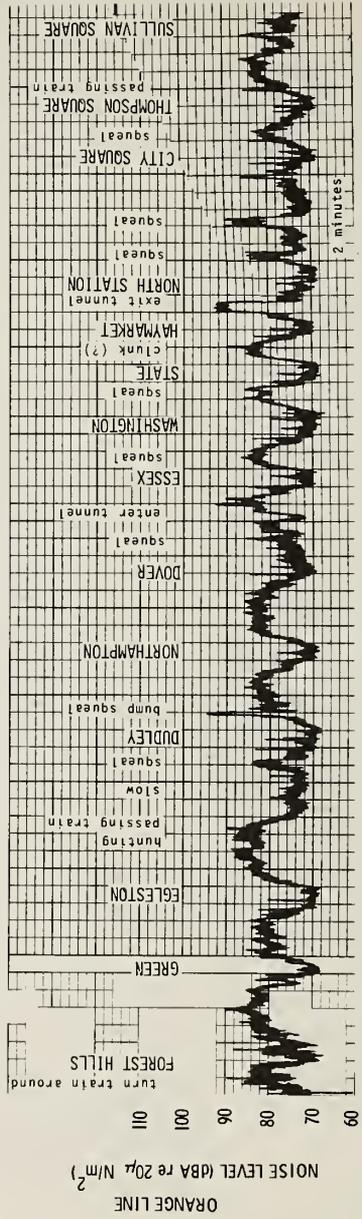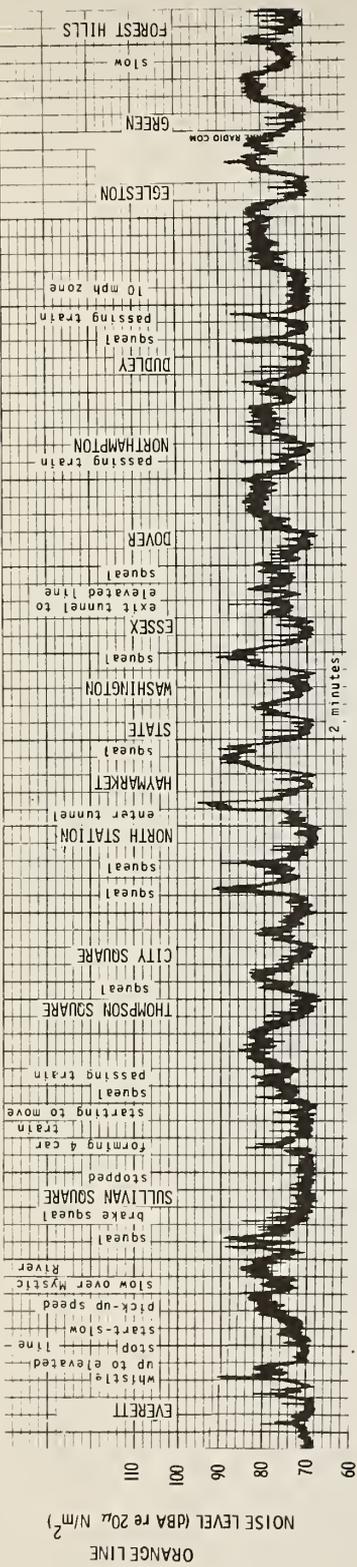
Figure A-2.   In-Car Noise Level Time History - Orange Line, Car No. 01105

A-4
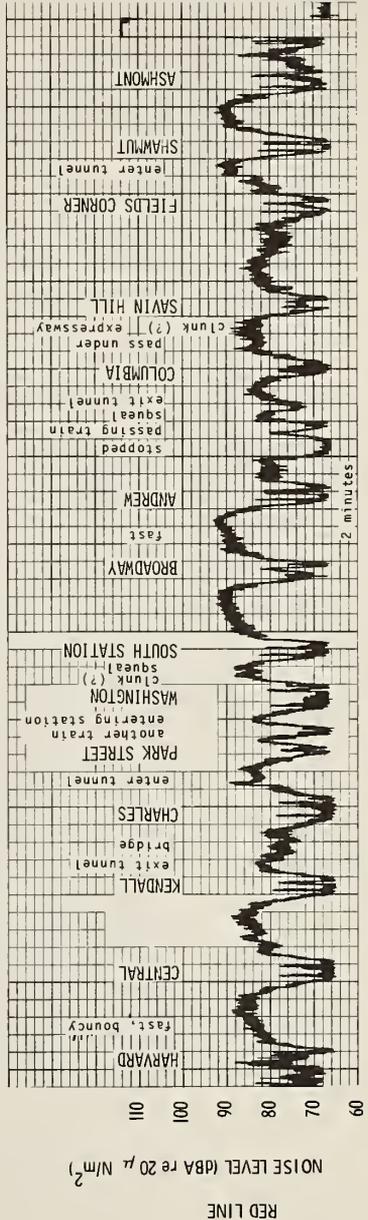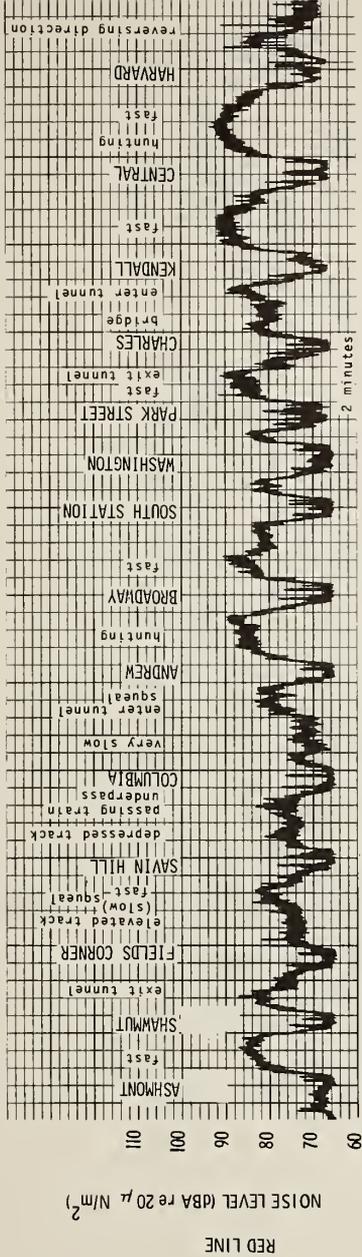
Figure A-3. In-Car Noise Level Time History - Red Line, Car No. 01480 (Bluebird)

A-5

Figure A-4. MBTA Blue Line Noise Measurement Summary

A-6

Figure A-5. MBTA Orange Line Noise Measurement Summary
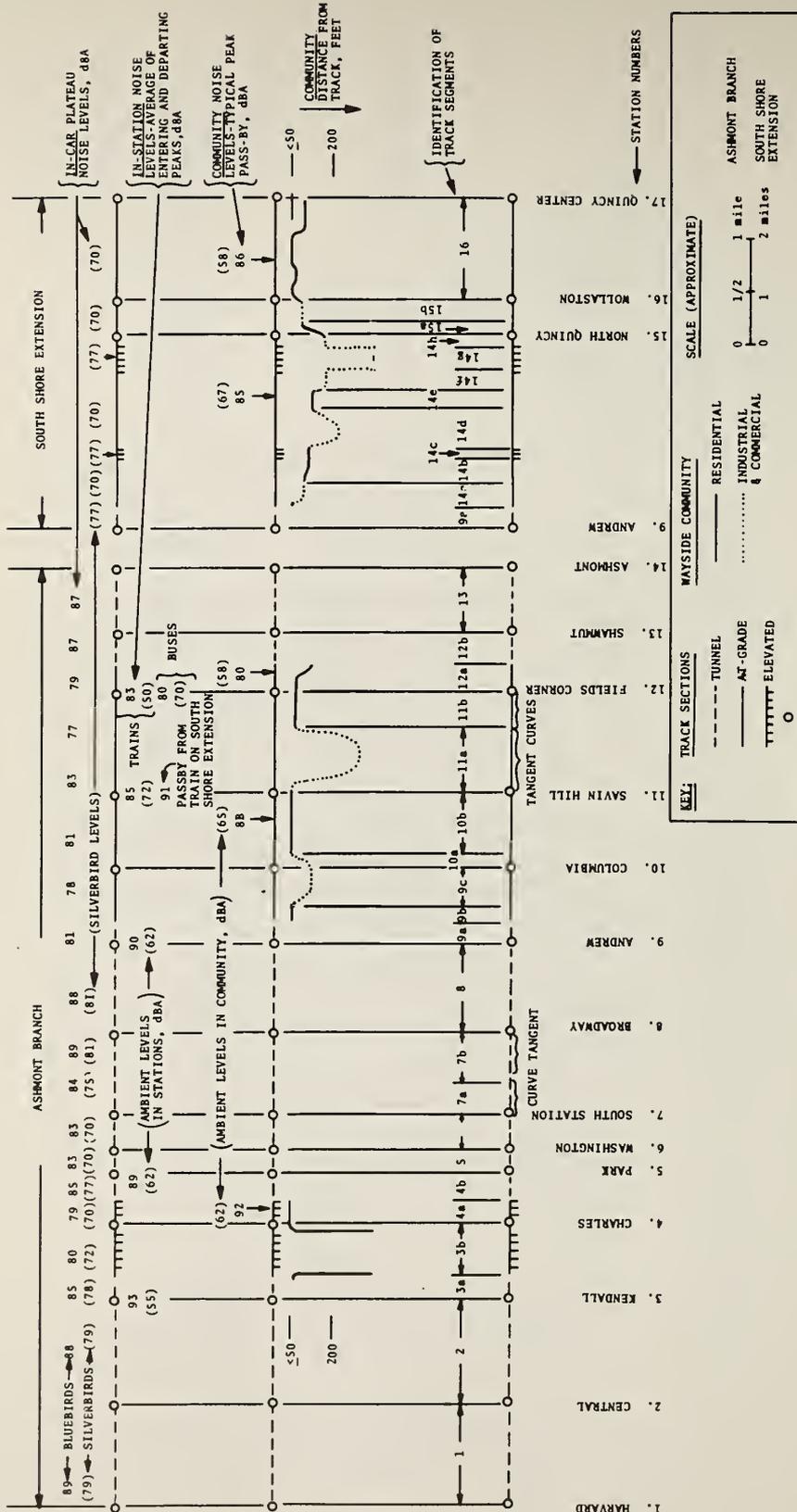
Figure A-6. MBTA Red Line Noise Measurement Summary

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

B-3

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

Select one of
these scenarios.

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 tech-
niques used for each scenario.

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.

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

A

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

B-5

D

Reference
Comment
No. 8

Reduce the contribution of each path
according to the combination tech-
niques 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   NO
desired level for   B
this scenario?

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 contri-
bution, the predicted noise levels
along each scenario.

END

B-6

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 brak-
    ing, acceleration, and even occassionally during steady
    tangent track operation.

APPENDIX D

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REFERENCES

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