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IN-SERVICE PERFORMANCE AND COSTS OF METHODS FOR CONTROL OF URBAN RAIL SYSTEM NOISE

Experimental Design

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16. Abstract

This report presents an experimental design for a project to evaluate four techniques for reducing wheel-rail noise on urban rail transit systems: (a) resilient wheels, (b) damped wheels, (c) wheel truing, and (d) rail grinding.

The design presents the project questions to be answered: (1) What reduction in noise can be achieved by the techniques, individually and in combinations? (2) What are the costs of the techniques?

The design gives data requirements for acoustic testing on the Southeastern Pennsylvania Transportation Authority Market-Frankford Line, as well as requirements for collection of non-acoustic data covering all United States rapid transit systems. It prescribes methods for analysis of the data, means for drawing inferences to answer the questions posed, and formats for presentation.

The design requires that the findings of the completed study be presented in a manner such that the information can be used by transit system personnel who may not have a background in acoustics of cost analysis.

17. Key Words
Noise, Resilient Wheels, Damped Wheels, Rail Grinding, Wheel Truing, Total Cost, Wheel-Rail Noise

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PREFACE

The interim report of Experimental Design, described herein, is part of a study of "In-Service Performance and Costs of Methods for Control of Urban Rail System Noise". The study, sponsored by the Rail Technology Division of the Urban Mass Transportation Administration, Office of Research and Development, is under contract with the Transportation Systems Center, Contract DOT-TSC-1053, for the Urban Rail Supporting Technology Program.

The Experimental Design phase is the first of a five-part study to evaluate methods and associated costs for control of urban rail system noise. It identifies those questions which the overall study is designed to answer and outlines the methods which will be used to analyze the data developed during the study.

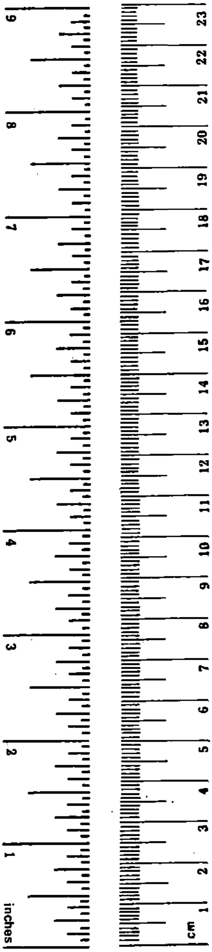
Upon completion, the study will provide findings on four methods of controlling wheel-rail noise, based on resilient wheels, damped wheels, wheel truing, and rail grinding for use in determining the optimum mix of wheel-rail noise control methods within the constraints of track and car conditions and budget limits.

The authors acknowledge the assistance of Robert Lotz, of the Transportation Systems Center, in the development of the experimental design and statistical inference procedures in the planning and analysis of the study. The contributions of Marshall Fritz, David Sanders, and Robert Watkins, of De Leuw, Cather & Company, and of George Paul Wilson and Armin T. Wright, of Wilson, Ihrig & Associates, are appreciated. The cooperation extended to the study team by officials of the Southeastern Pennsylvania Transportation Authority, during the Experimental Design phase, is gratefully acknowledged.

Approximate Conversions to Metric Measures

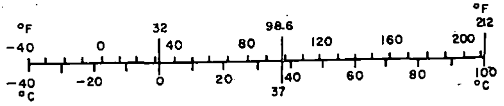
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

METRIC CONVERSION FACTORS



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SUMMARY

The results of the Experimental Design portion of Task 1 of a five-task program are presented in this interim report. Subsequent work will define the noise reductions attainable from the use of four wheel-rail noise control techniques (resilient wheels, damped wheels, wheel truing and rail grinding) and the total cost associated with each.

The purposes of this "Experimental Design Interim Report" are to:

1) Identify the questions the study is designed to answer.

2) Develop the parameters that will be used to evaluate the acoustic effectiveness and the associated costs of the noise control methods.

3) Outline the methods that will be used to analyze the evaluation parameters.

The methods that will be used to collect and manage the data will be presented in the "Test and Evaluation Plan Interim Report" that will be prepared subsequently.

QUESTIONS TO BE ANSWERED BY THE STUDY

The specific objective of this study is to develop data which will answer the following questions:

1) What reduction of wheel-rail noise in cars, in stations, and in the wayside community, can be achieved by using resilient wheels, using damped wheels, truing wheels, and grinding rails, or combinations thereof?

2) What are the total costs associated with each of the above techniques, or any combination thereof?

The data will be formatted to permit rail rapid transit systems' management to determine the answers to these questions for their specific systems, and to determine the combination of equipment and its recommended usage to realize the greatest benefit.

The study will develop qualitative information for use by rail rapid transit systems concerning:

a) The magnitude of any long-term changes in the performance, cost or safety of abatement equipment resulting from wear including year-round service in varied weather conditions.

b) The compatibility and constraints associated with each technique.

The study goals will be accomplished through two parallel efforts. First, an experimental program will be conducted to measure wheel-rail noise in car and at the wayside for most combinations of old and ground rail and factory new, trued and worn wheels of various designs. Second, an investigative program to gather the knowledge and experience of existing transit systems using any of the four noise control measures under study will be conducted.

Primary correlation will take place at the end of the study when the acoustical effectiveness and life expectancy of the measures will be weighed against the costs and problems associated with use of those methods. An optimization and or cost versus benefit analysis or both will be included in the final report.

In general, the testing procedure will consist of measuring and then comparing noise generated by the various combinations of the four noise control techniques on different track configurations. To illustrate, the study will determine if certain wheels significantly reduce noise on one type of track but are ineffective on others. Evaluation of other factors,such as ease of implementation, longevity, and required maintenance,will increase the usefulness of the information.

PARAMETERS TO EVALUATE ACOUSTIC EFFECTIVENESS

The primary acoustic quantity used in evaluating noise levels will be the A-weighted noise level (dBA). The A-weighted noise level is commonly used in most community noise evaluations and has been found to correlate with the subjective human evaluation of the noisiness of specific sounds.

Other appropriate acoustic parameters will be measured or calculated from tape recorded noise data.

Relative levels of reduction of wheel-rail noise achievable with the possible combinations of the four noise control treatments will be established by comparing the absolute quantities to a standard reference. Generally, the standard reference condition will be the untreated case: worn steel wheels on worn track. Attenuation will be evaluated as a function of speed, wheel and rail type, etc.

PARAMETERS TO EVALUATE COST

Cost data collected during the study will enable the investigators to evaluate the initial direct costs, operating and maintenance costs and residual values associated with ordinary steel wheels, wheel truing, rail grinding, wheel damping materials and resilient wheels.

The primary source of data on the total cost (initial plus operating and maintenance costs) for each of the noise control techniques will be observation and analysis of SEPTA operations and costs during the test phase of this study. The costs for labor, materials and equipment associated with each will be supplemented by provision for professional services and overhead costs where appropriate information can be developed.

The primary focus will be on the direct costs incurred implementing the noise control techniques. Indirect costs arising from secondary impacts, such as reductions in the number of cars available for service as a result of a resilient wheel installation program,will not be evaluated in detail.

ANALYSIS OF ACOUSTIC DATA

The techniques for analyzing the acoustic data outlined are tentative. Once the data has been collected and reduced, more efficient or appropriate methods may become apparent.

The acoustic data collected will include a very large number of measurements. The data will be carefully analyzed both by inspection and use of appropriate statistical techniques,such as least squares analysis and analysis of variance, to derive maximum information.

The statistical analysis will not replace engineering evaluation of the data. The statistical evaluation will be designed to formally validate conclusions drawn by inspection of the data and point to conclusions that are not obvious from inspection of the data.

Examples of the types of statistical analysis that may be performed are given in the report. Techniques illustrated are least squares, to determine best fit lines; and analysis of variance (ANOVA), to evaluate a linear model of the data. Both are standard techniques for analyzing and interpreting experimental data. Other statistical techniques also may be used in the final analysis of the data collected. Inspection of the measurement results will indicate the appropriate tests for the specific data.

The measurement conditions, analysis procedures and the type of information to be developed for ten test tracks on SEPTA are described in this report. The acoustic results for each test track section will be presented separately in the final report.

Typical data to be presented will include:

1) Tables of average attenuation for various wheel and rail conditions (average level referred to a standard reference level) for both interior and wayside measurement locations.
2) Plots of attenuation as a function of speed.
3) Representative A-weighted time histories of the train passbys.
4) Comparison and correlation of the results from the test track under consideration with the results from other test tracks.

ANALYSIS OF COST DATA

The cost data collected will be evaluated and the unit costs for the cost parameters developed. The unit costs will be used to finalize the method for use by transit systems to determine optimum allocation of resources among the four noise reduction techniques.

A method to examine logical combinations of resilient wheels, wheel damping, wheel truing, rail grinding, cost components, budget levels, and sensitivity factors will be developed to determine minimum life cycle costs. The life cycle costs for wheel-rail noise control will encompass the initial costs and maintenance costs for the projected system life analyzed.

The total cost associated with maintaining wheels and rails or providing alternate wheel systems for a particular rail rapid transit system will vary with the specific noise goals of the system, and will depend upon the characteristics of the system.

A methodology for applying the acoustical and cost data is presented in the body of the report.

1. INTRODUCTION

Urban rail rapid transit noise can be a significant annoyance to both patrons and communities adjacent to transit systems. One of the primary noise sources on a rail rapid transit system is the wheel-rail interaction. At normal operating speeds for many transit vehicles, wheel-rail noise dominates both the noise radiated to the wayside and the noise inside the transit cars. Effective noise control for rail transit thus requires affordable and predictable techniques for reduction of wheel-rail noise.

1.1 BACKGROUND

The U. S. Department of Transportation (DOT), Transportation Systems Center (TSC) is the systems manager for the Urban Mass Transportation Administration (UMTA) Urban Rail Supporting Technology Project. UMTA is sponsoring research to make available a technology for predictable control of acoustic noise and vibration in a form useful to present and planned urban rail systems. In addition to this study, integral elements of the overall program are:

1) Assessment of Urban Rail Noise and Vibration.
2) Track and Elevated Structure Noise and Vibration Control Technology.
3) Wheel-Rail Noise and Vibration Control Technology.

This interim report presents the experimental design for a field evaluation of four methods of controlling wheel-rail noise. Actual testing will be performed on the Market-

Frankford Line of the Southeastern Pennsylvania Transportation Authority (SEPTA), under conditions that closely approximate normal revenue operations.

1.2 STUDY PROGRAM

Although wheel-rail noise is known to be a major source of transit system noise, and some methods have proved effective in reducing wheel-rail noise, there is little documented information that can be used to evaluate the noise reduction potential for a given combination of noise abatement methods.

This five-task study is being conducted to fill this information gap through:

1) Evaluation of acoustical effectiveness of four noise control techniques.

2) Development of incremental cost information associated with implementation of the noise control methods.

3) Development of a cost/benefit methodology to evaluate possible combinations of acoustical techniques for use by rapid transit system managers to develop the best possible noise abatement program according to local conditions.

Findings of the completed study will be presented in a format which can be used by transit system personnel who may not have backgrounds in acoustics or cost analysis. The information will be straightforward, easily understood and readily applicable.

The specific noise abatement techniques that will be evaluated are based on the use of:

a) Resilient Wheels - Resilient wheels have a resilient material between the tire and hub that acts to damp resonant vibration of the wheel and reduce transmission of vibration to the web. Three types of resilient wheels will be included in the study.

b) Damped Wheels - Damped wheels are standard wheels that have had a vibration damping treatment to reduce wheel vibration.

c) Wheel Truing - Wheel truing is a process of grinding or machining wheel tire surfaces to a desired degree of smoothness to remove the nonuniformities created during operation.

d) Rail Grinding - Rail grinding is a process of grinding the running rail to eliminate roughness created by the passage of trains.

In general, the evaluation procedure will consist of measuring and then comparing noise generated by the various combinations of the four noise control techniques on different track configurations. To illustrate, the study will determine if certain wheels significantly reduce noise on one type of track, but are ineffective on others. Evaluation of other factors, such as ease of implementation, longevity, and required maintenance, will increase the usefulness of the information.

The cost analyses performed will investigate the relationship between noise reduction and costs.

Both the immediate and the long-term effectiveness and costs are to be evaluated, along with the initial capital cost attendant with each combination. The study, which began in July 1975, will continue to the fall of 1977.

The purposes of this "Experimental Design Interim Report" are to:

1) Identify the questions the study is designed to answer.
2) Develop the parameters that will be used to evaluate both the acoustic effectiveness and the associated costs of the various noise control methods.
3) Outline the methodology that will be used to analyze the evaluation parameters.

It is not the purpose of this report to give the details of the methods that will be used to collect and manage the data. Actual collection of data and the schedule of tests will be the subject of the "Test and Evaluation Plan Interim Report" that will be prepared subsequently.

2. STUDY OBJECTIVES

The specific objective of this study is to develop data which will answer the following questions:

1) What reduction of wheel-rail noise in cars, in stations and in the wayside community can be achieved by using resilient wheels, using damped wheels, truing wheels, and grinding rails, or combinations thereof?

2) What are the total costs associated with each of the above techniques, or combinations thereof?

The data will be formatted to permit rail rapid transit systems' management to develop the following information for their specific systems:

a) The potential reduction of wheel-rail noise which can be expected from the noise abatement techniques listed above.

b) The total cost of maintaining wheels and rails at a specified noise limit.

c) The combination of equipment and its recommended usage to realize the greatest benefit.

d) The minimum attainable noise level due to wheel-rail roughness excited noise.

The study also will develop information for use by rail rapid transit systems concerning:

1) The magnitude of any long-term changes in the performance, cost or safety of abatement equipment resulting from wear, including year-round service in varied weather conditions.

2) The compatibility and constraints associated with each technique.

Secondary goals of this program are:

a) Determine whether wheel-rail noise is the dominant source of noise and document the combined levels of other sources of noise.

b) Determine a simple single number parameter with which the acoustic effectiveness of the various noise control methods on the different types of track can be evaluated and compared.

c) Develop data on the effectiveness of the noise abatement techniques as a function of frequency.

d) Provide statistical analysis of the noise control data for each of the attenuation measures.

e) Develop data on relative attenuation in a form suitable for input to the cost versus benefit analysis.

f) Generate estimates of the effect of the schedule of wheel truing and rail grinding on the noise radiation.

g) Develop realistic cost estimates for the various noise abatement alternatives.

h) Provide a specific cost versus benefit analysis methodology that can be used by transit systems to estimate cost and noise attenuation for a noise abatement plan.

i) Provide a methodology that can be used by a transit system to estimate an optimum noise abatement plan for wheel-rail noise.

3. EVALUATION PARAMETERS

The specific parameters (testing, acoustic, cost and qualitative) that will be used to evaluate the acoustical effectiveness and the costs of the noise control techniques, and combinations thereof are presented in this section. Six sets of testing variables have been established to ensure that sufficient data concerning the noise control techniques are developed during the measurement program. Acoustic parameters will be used to evaluate the effect of altering the test variables. Interpretation of the cost parameters will establish the cost of the various noise control techniques. The qualitative parameters are variables that, although not specifically covered or controlled in this study, are recognized as possibly having an influence on the acoustical measurements, the implementation of the methods on other transit systems, and the transferability of the results to other systems.

3.1 TESTING VARIABLES

The specific conditions that comprise the variables for the testing program can be summarized as follows:

1) Wheel Type
    - a) Ordinary steel, worn and new
    - b) Penn Bochum resilient
    - c) Acousta-Flex resilient
    - d) Damped standard
    - e) SAB resilient.
2) Wheel Condition
    - a) New

    - b) Worn by one year normal revenue service
    - c) Trued.

3) Rail Types and Locations
    - a) Tangent-welded - elevated, ballast and tie
    - b) Tangent-jointed - elevated, ballast and tie
    - c) Tangent-welded - subway, concrete trackbed
    - d) Tangent-jointed - subway, concrete trackbed
    - e) Station, subway
    - f) Station, elevated
    - g) Short radius curve - subway
    - h) Short radius curve - at grade
    - i) Rail frog.

4) Rail Conditions
    - a) Worn
    - b) Ground smooth
    - c) Joints aligned.

5) Measurement Locations
    - a) Inside car
    - b) Wayside
    - c) On station platforms.

6) Train Speed (tangent track only; for curves and stations, normal operating speed will be used)
    - a) 40 km/h (25 mph)
    - b) 60 km/h (37 mph)
    - c) 80 km/h (50 mph), or maximum feasible speed if 50 mph is not possible.

A comprehensive evaluation of the effectiveness of various methods of reducing wheel-rail noise requires that a large number of variables be considered. All the wheel sets except the worn standard wheels will be initially tested in their new "factory-fresh" condition, then after one year of deterioration in normal revenue service. One type of resilient wheel, the damped wheels and the new standard wheels will be tested after being smoothed and trued with the wheel truing machine. Each set of wheels will be tested on various types of track and for different rail conditions. Measurements will be made for varying train speeds and for both car interior and wayside noise.

3.2 ACOUSTIC PARAMETERS

The primary acoustic quantity used in evaluating noise levels of the trains under the various test conditions will be the A-weighted noise level (dBA). The A-weighted noise level is commonly used in most community noise evaluations and has been found to correlate with the subjective human evaluation of the noisiness of specific sounds.

According to an earlier report in this series of studies of wheel-rail noise, "Based on all the information presently available, *the maximum A-weighted sound level during a train passage* is the best choice for evaluating the efficiency of the various noise control measures to be studied in the wheel-rail noise project".*

Continuous magnetic tape recordings of train passby noise will be made at the measurement locations. The following quantities will be derived from the continuous record.

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* Schultz, T. J., Development of An Acoustic Rating Scale for Assessing Annoyance Caused by Wheel/Rail Noise in Urban Mass Transit, DOT Report No. UMTA-MA-06-0025-74-2, February 1974.

L_A - *The energy average A-weighted noise level over a specific period of time.* L_A will be a true root mean square (RMS) level determined with a real time analyzer. The RMS level of a randomly varying quantity v(t) is defined as:

$$L_{RMS} = 10 \log \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} v^2 (t) \, dt. \qquad [3\text{-}1]$$

This can be shown to be equivalent to:

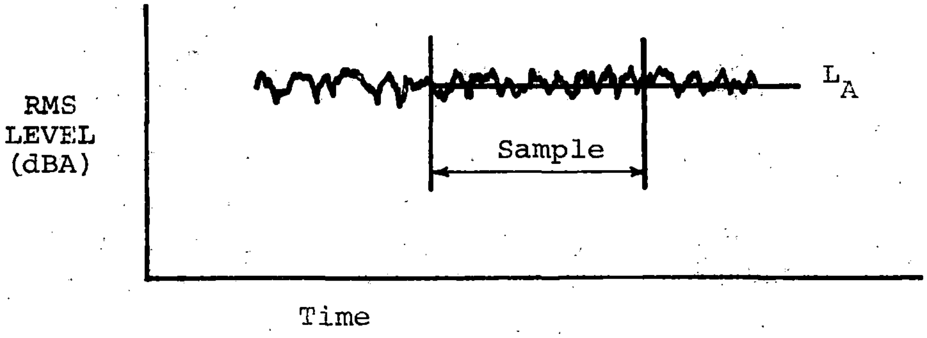
$$L_{RMS} = 10 \log \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} 10^{L(t)/10} \, dt' \qquad [3\text{-}2]$$

where L(t) is the time varying noise level and is defined as:

$$L(t) = 10 \log v^2(t). \qquad [3\text{-}3]$$

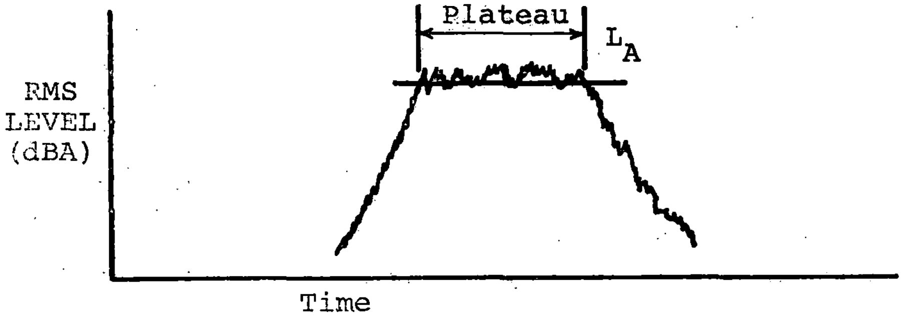
The second form of the equation for L_{RMS} is the same as the definition of the energy equivalent noise level, L_{EQ}. L_{EQ} is often used in the evaluation of community noise. L_{EQ} and L_{RMS} are equivalent with the only difference being that L_{EQ} typically refers to a longer sample period, e.g.,10 minutes to 24 hours, while L_{RMS} is normally evaluated over a time period consisting of a fraction of a second up to a few seconds.

The time period over which L_A is determined will vary somewhat depending on the form of the noise level time history. For interior noise, the noise level will be the energy average of the RMS level during any 1 to 4 second period while the train is on the experimental track section.



SKETCH OF TYPICAL INTERIOR-NOISE SAMPLE

The sketch below illustrates the noise level for a typical passby at a wayside location adjacent to tangent track. In this case, L_A will represent the energy average of the RMS level for the plateau.



SKETCH OF TYPICAL WAYSIDE-NOISE SAMPLE

The wayside noise level for wheel squeal noise on short radius curves will not have a well defined plateau. Due to the rapid and wide variation of squeal noise level on short radius curves, a relatively long integration time period (four to sixteen seconds) will be used to determine the energy average (RMS) noise levels.

L_{IMP} - *The peak impulsive noise level due to rail joints or frogs.* This quantity is included since impulsive noise has a different character than continuous random noise. As such, the annoyance factor of wheel-rail noise at rail frogs or joints could be underestimated if the impact noise is not analyzed in addition to L_A. L_{IMP} will supplement, not replace L_A at joints and frogs. The method used to measure L_{IMP} will be detailed in the"Test and Evaluation Interim Report".

L_E - *The total acoustic energy during a test sample.* L_E will be used to evaluate the samples taken at the elevated and subway stations where a car stop of indeterminate duration will sometimes occur. A total energy evaluation will remove the influence of the length of the stop (within reasonable limits) and the distance the train is from the station when the sample is started. To provide a measure that more closely corresponds to typical noise levels during the sample, the energy may be referenced to a standard time period. The result would then be:

$$L_E = L'_E - 10 \log T, \qquad [3\text{-}4]$$

where L'_E is the total energy for the passby, and T is the reference time for the event. If the train is typically audible for about 30 seconds, using T = 30 seconds would make L_E approximately equal to the energy equivalent level, L_{EQ}, during the time the train is audible. Although the relative levels of L_E for different conditions would remain unchanged, the significance of the measure would be more easily understood.

Using the appropriate quantity defined above, L_A, L_{IMP}, or L_E, the results of the various passbys for each wheel-rail combination will be analyzed to develop the following quantities which will represent the noise level for each specific combination of conditions.

L(V) - *Noise level,* L_A, *as a function of speed* (V). The least squares method will be used to fit the data to a curve of the following form:

$$L(V) = A \log V + B, \qquad [3\text{-}5]$$

where A and B are constants. Previous measurements have shown that above 20 mph, L_A is almost linearly proportional to the log of speed. Hence, the data can be expected to fit this curve very closely.

$L_{IMP}(V)$ - *Impulsive noise level as a function of speed.* The results of previous theoretical analyses of wheel-rail impulsive noise indicate that in many situations, the wheel-rail impact noise level will be proportional to 20 log V, at least for low speeds.* However, it will be necessary to inspect the data before it can be established that this is a reasonable characterization.

L_{AV} - *The average noise level.* When various speeds are evaluated over a test track section, L_{AV} will be the noise level averaged over the speed range of interest. When the noise level at each test speed has been determined, one manner in which the average level may be evaluated is given by:

$$L_A = \frac{1}{V_2 - V_1} \int_{V_1}^{V_2} L(V)\, dv, \qquad [3\text{-}6]$$

where V_1 and V_2 are the high and low limits, respectively, of the speed range. When the level is proportional to the log of speed, it can be shown that when V_1 = 25 mph and V_2 = 50 mph,

$$L_{AV} = 1.56\, A + B. \qquad [3\text{-}7]$$

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* Remington, P. J. et al, Wheel/Rail Noise and Vibration, DOT Report No. UMTA-MA-06-0025-75-10, May 1975.

It should be noted that when L_{AV} is determined as indicated above, it can be considered as equivalent to the level on the regression line at 36 mph, that is:

$$L_{AV} = L(36.3 \text{ mph}) = A \log 36.3 + B. \qquad [3\text{-}8]$$

Note that in situations where speed is not varied over a test track section, L_{AV} will be the arithmetic average of all the passbys.

$L_{IMP(AV)}$ - *The average of the maximum impulsive noise level observed over the speed range.* Assuming that a curve can be fitted to the $L_{IMP}(V)$ data, $L_{IMP(AV)}$ will be derived in the same manner as L_{AV}. The manner in which the average is calculated may, however, be determined by the form of the data.

$L_{E(AV)}$ - *The arithmetic average of the energy levels of the passbys.*

These quantities will be used to characterize the absolute noise levels for the various test track sections and wheel types. Determining the relative reduction of wheel-rail noise that can be achieved with each of the possible combinations of noise control techniques is a primary goal of this study. Relative levels of reduction will be established by comparing the absolute quantities to a standard reference. Generally, the standard reference condition will be worn steel wheels on worn track. The standard wear period for both the steel wheels and the track will be one year. The test track arrangement and the data collection methods have been set up to minimize the random variation of the measured attenuation quantities.

The elevated tangent welded and jointed test tracks and the surface curve test track all include control track sections that will remain unchanged during the entire test program, except, of course, for the normal deterioration over the duration of the project. These control track sections will not have been ground smooth or aligned for approximately one year prior to the testing. A two-car set of wheels that has been worn for at least a one-year period in normal revenue service also will be included in the testing. The test data for the worn wheels and worn rail in the control sections will be evaluated to determine if it is possible to use the results as a standard reference condition. If the noise radiation with wheels and rail worn by one year of revenue service is not significantly different from noise radiated after two years of service, the worn wheels and rail will be assumed to be a stable reference condition. The statistical assumption that essentially the same measurement has been taken during each measurement phase would aid in identification of variations due to uncontrolled variables, such as climatic conditions. If the change in noise radiation characteristics between a one-year wear period and a two-year wear period is significant, but small and predictable, it may still be possible to use the results during each test phase with worn wheels and rail as a stable reference condition.

The acoustic evaluation parameters that will be used to characterize the noise at each test track and each measurement location are summarized in Table 3-1. It should be re-emphasized that the attenuation of any specific combination of the noise control techniques will be characterized by changes in the absolute evaluation parameters compared to the appropriate standard reference condition.

In this study,the primary point of interest is the attenuation as a function of speed, wheel and rail type, etc., instead of the absolute values. The attenuation referred to is

TABLE 3-1. ACOUSTIC EVALUATION PARAMETERS FOR WHEEL-RAIL NOISE

Track Construction	Rail Type	Measurement Location	Measured Variable	Acoustic Evaluation Parameters
Aerial............	Tangent-welded	Wayside	L_A	$L(V)$, L_{AV}
Aerial............	Tangent-welded	Interior	L_A	$L(V)$, L_{AV}
Aerial............	Tangent-jointed	Wayside	L_A L_{IMP}	$L(V)$, L_{AV} $L_{IMP}(V)$, $L_{IMP(AV)}$
Aerial............	Tangent-jointed	Interior	L_A L_{IMP}	$L(V)$, L_{AV} $L_{IMP}(V)$, $L_{IMP(AV)}$
At-grade..........	Curve	Wayside	L_A	L_{AV}
At-grade..........	Curve	Interior	L_A	L_{AV}
Subway............	Tangent-welded	Interior	L_A	$L(V)$, L_{AV}
Subway............	Tangent-jointed	Interior	L_A L_{IMP}	$L(V)$, L_{AV} $L_{IMP}(V)$, $L_{IMP(AV)}$
Subway............	Curve	Interior	L_A	L_{AV}

the reduction of noise that will be realized when a specific noise abatement treatment is implemented. The treatment could be any combination of the noise abatement measures investigated in this project.

The attenuation will be considered to be:

$$\triangle L_A = L_A - L_{REF}, \qquad [3\text{-}9]$$

where L_A is the measured absolute noise level, L_{REF} is the reference level, and $\triangle L_A$ is the attenuation.

Of course, L_{REF} will be a function of speed of the form:

$$L_{REF} = A \log V + B, \qquad [3\text{-}10]$$

where A, B are constants, and V is the train speed.

The level L_{REF} refers to the average noise level for the reference condition of worn steel wheels on worn track with an approximately one-year wear period for both. The constants A and B will be determined from the measurement of the reference condition using the least squares method. Since the values of attenuation for a specific test track will all be determined using the same values of L_{REF}, the transformation will not result in any loss of information about the variation of the data.

3.3 EVALUATION OF RAIL ROUGHNESS

Although the exact methodology is not yet established, the roughness of the wheels and rails will be measured periodically. The roughness will be measured via the analog output from a probe that is moved at constant speed over the wheel or rail surface. The analog output signal will be analyzed to determine the spectrum of the vertical velocity of the probe. The vertical velocity spectrum will represent the rate of change of the surface for the constant horizontal velocity. The results will be scaled to give the spectrum of the rate of change of the surface for the train speeds tested in the study.

It is expected that at a specific train speed the rate of change of the surface contours of the wheels and rails are parameters that will correlate with the vibration levels of the wheels and rails, and hence will correlate with the radiated wheel-rail noise. The parameter used to evaluate wheel and rail roughness will be the probe vertical velocity spectrum for a horizontal speed equal to the train speed.

The wheel and rail roughness results will be analyzed to derive a single number measure of roughness, in the same manner as the acoustic data. For convenience in this report, the single number measure of roughness will be referred to as L_{RUF}. To facilitate more detailed investigations, the spectrum of the roughness in the form of 1/3-octave band levels also will be measured. However, it is L_{RUF}, the single number overall measure of roughness, that will be used to characterize the rail roughness. The exact manner in which L_{RUF} will be calculated has not yet been determined. Although the final form will largely depend on the results, it is tentatively planned to use the A-weighting network to combine all of the 1/3-octave band velocity levels into L_{RUF}. It is expected that the wheel-rail vibration levels, hence the radiated A-weighted noise levels, will show a strong correlation to L_{RUF} for the wheels and rail. It is also anticipated that the L_{RUF} will be a true indicator of the deterioration of the track due to wear.

3.4 COST PARAMETERS

Cost data collected will enable the investigator to evaluate the initial direct costs (Y_1), operating and maintenance costs (Y_2), and residual values (Y_3) (as applicable) associated with ordinary steel wheels, wheel truing, rail grinding, wheel damping materials and resilient wheels. The parameters for which costs will be developed are summarized in the list below:

1) Y_1 = initial direct costs
    a) X_1 = initial cost wheel truing machine
    b) X_2 = initial cost rail grinding machine
    c) X_3 = initial cost resilient wheels
    d) X_4 = initial cost damped wheels.
2) Y_2 = operating and maintenance costs
    a) X_5 = total cost wheel truing
    b) X_6 = total cost of inspecting resilient wheels
    c) X_7 = total cost of inspecting damped wheels
    d) X_8 = total cost of grinding rail
    e) X_9 = total cost of replacing resilient wheels
    f) X_{10} = total cost of replacing wheel damping
    g) X_{11} = total cost of replacing standard wheels
    h) X_{12} = total cost of inspecting standard wheels.
3) Y_3 = residual value
    a) X_{13} = residual value of wheel truing machine
    b) X_{14} = residual value of rail grinding machine
    c) X_{15} = residual value of resilient insert and tire (does not include wheel hub if replacement is not required)

d) X_{16} = residual value of wheel damping material

e) X_{17} = residual value of steel wheel.

The components of each parameter and the procedure for calculating the total costs are detailed in the following sections.

3.4.1 Initial Direct Costs (Y_1)

$$Y_1 = X_1 + X_2 + X_3 + X_4, \qquad [3\text{-}11]$$

X_1 = total initial direct cost of wheel truing machine, includes cost of acquiring and installing;

X_2 = total initial direct cost of rail grinding machine, includes cost of acquisition;

X_3 = total initial direct cost of resilient wheel (cost to be calculated for each type of resilient wheel)

$$= R_m + R_l + R_c = (W \times K) + (T_r \times K \times LR_r) + R_c, \qquad [3\text{-}12]$$

where W is the net materials cost per car for resilient wheels, K is the number of cars on the system, T_r is the labor required per car to install wheels, LR_r is the labor rate, including fringe benefits, and R_c is the shop cost for installing resilient wheels;

X_4 = total initial direct cost of damped wheels

$$= D_m + D_l + D_c$$

$$= (D \times K) + (T_d \times K \times LR_d) + D_c, \qquad [3\text{-}13]$$

where D is the net materials cost per car for damped wheels, T_d is the labor required per car to install damping material, and LR_d is the labor rate, including fringe benefits, and D_c is the shop costs for installing damping on wheels.

3.4.2 Annual Operating and Maintenance Costs (Y_2)

$$Y_2 = X_5 + X_6 + X_7 + X_8 + X_9 + X_{10} + X_{11} + X_{12}, \quad [3\text{-}14]$$

X_5 = total cost of truing wheels

$$= T_t \times K_t \times LR_t, \quad [3\text{-}15]$$

where T_t is the labor required per car to true wheels, K_t is the number of cars to be trued annually, and LR_t is the labor rate, including fringe benefits;

X_6 = total cost of inspecting resilient wheels

$$= T_i \times K_{ir} \times LR_i \quad [3\text{-}16]$$

where T_i is the labor required per car to inspect resilient wheels, K_i is the number of cars to be inspected annually, and LR_i is the labor rate, including fringe benefits;

X_7 = total cost of inspecting damped wheels

$$= T_i \times K_{id} \times LR_i, \quad [3\text{-}17]$$

where T_i is the labor required per car to inspect damped wheels, K_{id} is the number of cars to be inspected annually, and LR_i is the labor rate, including fringe benefits;

X_8 = total cost of grinding rail

$$= (T_g \times M_g \times LR_g) + GR_m \qquad [3\text{-}18]$$

where T_g is the labor required per mile to grind rail, M_g is the miles of rail to be ground annually, LR_g is the labor rate, including fringe benefits, and GR_m is the net material cost to grind rail;

X_9 = total cost of replacing tire and resilient insert of resilient wheel

$$= RR_1 + RR_m$$

$$= (T_{rr} \times K_{rr} \times LR_{rr}) + (W_{rr} \times K_{rr}), \qquad [3\text{-}19]$$

where T_{rr} is the labor required per car to install tire and resilient insert, K_{rr} is the number of cars requiring replacement annually, L_{rr} is the labor rate, including fringe benefits and W_{rr} is the net materials cost per car for new tires and inserts;

X_{10} = total cost of removing and replacing wheel damping

$$= DR_1 + DR_m$$

$$= (T_{dr} \times K_{dr} \times LR_{dr}) + (W_{dr} \times K_{dr}), \qquad [3\text{-}20]$$

where T_{dr} is labor required per car to remove and replace wheel damping, K_{dr} is the number of cars requiring replacement, LR_{dr} is the labor rate, including fringe benefits and W_{dr} is the net materials cost per car for new damping material;

X_{11} = total direct cost of replacing standard wheels

$$= S_m + S_1 + S_c$$

$$= (S \times K_s) + (T_s \times K_s \times LR_s) + S_c, \qquad [3\text{-}21]$$

where S is the net materials cost per car for standard wheels, K_s is the number of cars requiring replacement, T_s is labor required per car to install standard wheels, LR_s is the labor rate, including fringe benefits, and S_c is the annual shop cost for replacement of standard wheels;

X_{12} = total cost of inspecting standard wheels

$$= T_s \times K_s \times LR_i, \qquad [3\text{-}22]$$

where T_s is the labor required to inspect standard wheels, and LR_i is the labor rate, including fringe benefits.

3.4.3 Residual Values (Y_3)

$$Y_3 = X_{13} + X_{14} + X_{15} + X_{16} + X_{17}. \qquad [3\text{-}23]$$

As applicable to each technique, an offset cost would be considered at the time of replacement and at the end of the hypothetical system life. For each material or machine, there might be an associated scrap or reuse value.

Using a straight-line method of computation, the formula for computing the pertinent residual values at the end of the system life is:

$$RV = \frac{.75\ (OC) - VUL}{YUL-1} \times RYUL + VUL, \qquad [3\text{-}24]$$

where RV is the residual value, OC is the original cost, VUL is the value at the end of useful life, YUL is the years of useful life, and RYUL is the remaining years of useful life,

X_{13} = RV of wheel truing machine

X_{14} = RV of rail grinding machine

X_{15} = RV of resilient insert and tire

X_{16} = RV of wheel damping material

X_{17} = RV of steel wheel.

3.5 QUALITATIVE PARAMETERS

Although the various parameters summarized above include a very large number of variables and conditions, there are additional factors that can influence the radiation of wheel-rail noise and the practicality of implementing the methods on specific transit systems.

One concern is the safety of transit system employees and patrons. During the testing phase, close watch will be kept for any incidents which might be related to the noise control methods. Flammability, toxicity and compatibility with system design in areas of clearance, signalling, power and braking also will be investigated.

Below is a list of a number of parameters that will not be evaluated with direct measurement. Instead, a qualitative evaluation of these parameters will be performed. The information will be gathered largely by a survey of SEPTA, and other systems where possible:

1) Weather and climatic effects.
2) Thermal effects.
3) Dust, dirt and water.
4) Oil and grease.
5) Ozone.
6) Passenger loading conditions.
7) Weight of car.
8) Superelevation.
9) Wheel suspension elasticity.
10) Wheel spacing.
11) Track gauge (tangent and curve).
12) Wheel roundness and wobble.
13) Roadbed type (open deck elevated, ballast/ties, fasteners or direct fixation, tie in concrete).
14) Brake system (tread, disc, slip resistant).
15) Curve lubrication systems.
16) Flammability.
17) Station location, spacing.
18) Track gradient.
19) Curve radius.
20) System compatibility.

4. DATA COLLECTION

4.1 EXPERIMENTAL AND INVESTIGATIVE PROGRAMS

The collection of data will be accomplished through two parallel efforts. First, an experimental program will be conducted in which wheel-rail noise in the car and at the wayside will be measured for most combinations of old and ground rail and factory new, trued and worn wheels of various designs; second, an investigative program which gathers the knowledge and experience of existing transit systems using any of the four noise control measures under study will be conducted.

These parallel efforts will be coordinated to assure that pertinent data are being collected. However, primary correlation will take place at the end of the study when the acoustical effectiveness and life expectancy of the measures will be weighed against the costs and problems associated with use of those methods. An optimization and or cost-benefit analysis will be included in the final report.

4.2 ACOUSTICAL DATA

The study program has been designed so that the selection of test treatments, cars, track, operating conditions, measurement techniques and analysis methods will lead to comprehensive, numerical data on the evaluation parameters defined in the previous section. Since the purpose of this report is to outline the data reduction and analysis methodology, only a simple summary of some of the most important features of the test program is included below. The details of the testing program will be outlined in the "Test and Evaluation Plan Interim Report" that will be prepared as the next phase in this study.

The principal features of the test program are:

1) Use of unmodified "control" sections of track at each major test site: tangent-jointed, tangent-welded and turnaround.

2) Use of a control train with worn standard wheels which are not trued during the entire program, thus providing information on wheel aging for a period greater than the duration of the program.

3) Use of wheel vibration dampers.

4) Use of two-car test trains to ensure acquisition of data representative of multi-car trains.

5) Limited testing with single cars sufficient to ensure continuity of the program in the event of accident or failure of one of the test cars.

6) Purchase of limited spare resilient wheels for use as replacements in the event of an individual wheel failure.

7) Use of an existing, well proven, integrated data reduction, processing, storage, analysis, and plotting system providing

    a) Real time 1/3-octave band analysis

    b) Data storage on digital magnetic tape

    c) Digital data management and analysis

    d) Digitally controlled plotting of data and trend curves.

8) The derivation of curves to assist transit systems in selection of optimum allocation of resources between the four noise reduction techniques under study.

The measurement program is arranged to take maximum advantage of the possible combinations of new or trued and worn wheels and rails on various types of way.

The preliminary test plan has been developed to minimize the number of times the SEPTA Speno rail grinder and milling type of wheel truing machine must be used while still assuring that all useful combinations of conditions are tested. Noise from factory new, lathe turned wheels also will be measured.

4.3 SURVEY OF OTHER SYSTEMS

Concurrent with the development and execution of the testing program, a survey of existing and soon to be operating transit systems will be conducted to obtain data concerning their experience with any or all of the four noise control techniques being evaluated. Additionally, data on the scope of their operations, equipment operated, previous noise abatement experience, and wheel and rail maintenance practices will be obtained. Manufacturers and suppliers of equipment and materials pertaining to each of the noise control techniques also will be contacted. The information developed will further assist in the identification and quantification of those factors which affect cost and performance of each technique. The following transit systems will be contacted:

1) New York City Transit Authority (NYCTA).
2) Port Authority Trans Hudson Corporation (PATH).
3) Port Authority Transportation Company (PATCO).
4) Cleveland Transit System (CTS).
5) Chicago Transit Authority (CTA).
6) Bay Area Rapid Transit (BART).
7) Massachusetts Bay Transportation Authority (MBTA).
8) Toronto Transit Commission (TTC).
9) Washington Metropolitan Area Transit Authority (WMATA).
10) Metropolitan Atlanta Regional Transportation Authority (MARTA).

The cooperation of the Transit Development Corporation in facilitating this effort is anticipated.

No significant data for comparison with the SEPTA noise and vibration control study are anticipated from the MARTA system, since it is not presently in operation. However, some data should be available from the WMATA system since it will go into operation during the study period. It will be useful, for information purposes, to note the proposed method of noise and vibration control along with the anticipated and available results for these two systems.

A detailed questionnaire and an explanation of the objectives of the study will be submitted to each system. Interviews with engineering, car equipment and noise control personnel will be conducted. Coordination with the testing program will assure that pertinent data is being developed so that, upon completion of the test program, the acoustical effectiveness and life expectancy may be weighed against the costs and problems associated with use of the four noise control techniques.

Some systems may already have equipment and operational techniques which are not compatible with the techniques of noise control that this study is observing. Adaptability to other systems may be determined by operating characteristics and other variables which may emerge during the study. Such information will be developed as a result of this survey.

4.4 COST-ANALYSIS DATA

The primary source of data on the total cost (initial plus operational and maintenance costs) for each of the noise control techniques will be the observation and analysis of

SEPTA operations and costs during the test phase of this study. The costs for labor, materials and equipment associated with each will be supplemented by provision for professional services and overhead costs where appropriate information can be developed. Additional data sources will be the rapid transit systems contacted during the survey and suppliers of the various materials and equipment required to install, maintain or operate the resilient wheels, the damped wheels, the wheel truing machines and the rail grinding machines.

The focus will be primarily on the direct costs which are incurred as an immediate result of the various noise abatement techniques. Indirect costs that arise from secondary impacts, such as reductions in the number of cars available for service as a result of a resilient wheel installation program, will not be evaluated in detail.

Total labor costs, including direct labor, supervision and overhead, will be developed for the techniques as follows:

1) Resilient Wheels - cost to acquire, install, inspect and maintain during the expected life of the wheel.

2) Damped Wheels - cost to acquire, install and maintain wheel damping on standard wheels.

3) Rail Grinding - cost to operate and maintain rail grinding equipment, including changeover or regauging operations for multi-gauge lines.

4) Wheel Truing - cost to true wheels to specified tolerances.

Material costs will include the cost of purchase and delivery of wheels and damping materials and the cost of grinding wheels, stones, fuel, oil, electricity, cutter heads, etc., for the rail grinding and wheel truing machines.

Equipment costs will include the cost to obtain new and or additional rail grinding and wheel truing machines necessary to perform the optimum level of resurfacing.

The data developed on labor costs will include estimated man-hours for initial installation and maintenance costs as well as average labor costs in dollars.

For the purpose of meaningful cost comparisons, 1976 will be used as the base year, during which the testing on the SEPTA Market-Frankford line will be done.

Table 4-1 summarizes the anticipated methods for collecting data on the cost parameters.

TABLE 4-1. COST PARAMETERS AND METHOD OF DATA COLLECTION

Evaluation Parameter	Method of Data Collection
X_1....................	Survey of manufacturers, rapid transit lines,and SEPTA
X_2....................	Survey of manufacturers, rapid transit lines,and SEPTA
X_3....................	Survey of manufacturers, rapid transit lines,and SEPTA
X_4....................	Survey of manufacturers, rapid transit lines,and SEPTA
X_5....................	Survey of rapid transit lines, and SEPTA
X_6....................	Survey of rapid transit lines, and SEPTA
X_7....................	Survey of rapid transit lines, and SEPTA
X_8....................	Survey of rapid transit lines, and SEPTA
X_9....................	Survey of manufacturers, rapid transit lines,and SEPTA
X_{10}....................	Survey of manufacturers, rapid transit lines,and SEPTA
X_{11}....................	Survey of manufacturers, rapid transit lines,and SEPTA
X_{12}....................	Survey of rapid transit lines, and SEPTA
X_{13}....................	Survey of rapid transit lines, and SEPTA
X_{14}....................	Survey of rapid transit lines, and SEPTA
X_{15}....................	Survey of rapid transit lines, and SEPTA
X_{16}....................	Survey of rapid transit lines, and SEPTA
X_{17}....................	Survey of rapid transit lines, and SEPTA

5. DATA ANALYSIS

5.1 GENERAL METHODS

The general methods that will be used to analyze the data and reduce it to a form suitable for satisfying the study objectives is presented. The first step in the analysis will be to reduce the raw data to develop the evaluation parameters presented in Section 3. The methods used to compare the various parameters and to develop the cost versus benefit methods is detailed below.

The techniques outlined for analyzing the data should be considered tentative. Once the data has been collected and reduced, more efficient or appropriate methods may become apparent.

5.2 ANALYSIS OF ACOUSTIC DATA

An enormous quantity of acoustic data will be collected. The methods used to reduce and analyze this data will, to a large extent, determine how useful the results will be in aiding transit systems to evaluate the possible application of the noise control methods. Since it is a primary goal of this study to provide engineering data that can be applied by managers and engineers who are not noise control technology specialists, the analysis will attempt to reduce the large quantity of acoustic data to the simplest forms possible.

Although the absolute values of the various acoustic evaluation parameters will be determined and reported, it is the relative values, i.e., the attenuation from the existing situation, that will be of most interest. The test schedule will include control sections of track contiguous to three of the test tracks, and one train which already has worn wheels at the start of the study. The control sections and worn wheels will receive no grinding or truing throughout the study. Since the wheels and rail will continue to wear during the study, they will provide data on wear periods greater than one year.

Measurements on the pre-worn wheels on the control track sections will be included in most of the test series. The control sections will help to identify any anomalies in the test data and help provide a constant reference.

Although the various noise control methods will be assessed using the A-weighted levels, the 1/3-octave band levels also will be available. Due to the complexity of the 1/3-octave data, it will not be possible to incorporate the results into an overall evaluation of the noise control methods. However, the 1/3-octave band data will be invaluable in a more detailed investigation of the mechanisms of noise radiation and noise control. The A-weighted levels give no information about the spectral composition of the noise signal and hence only a general indication of the effectiveness of a noise control method.

A single number parameter, ΔL_{AV}, will be used to present a straightforward, easily understood, evaluation parameter of the relative effectiveness of the various combinations of noise control methods. As defined in Section 3, it is merely the difference between the average value for a specific set of conditions on a test track and the average value for the test track standard reference condition. The average level, L_{AV}, will be determined in somewhat different manners for the various test tracks.

The average attenuation, ΔL_{AV}, will be a valid comparator of the various conditions of a preliminary basis only. That is, the average value will not indicate if a particular method is more effective at high speeds than at low speeds. A more thorough investigation of the data will be necessary to reveal such results.

It is expected that either ΔL_{AV} or quantities derived from ΔL_{AV} will be used as the acoustical input to the cost versus benefit analysis.

5.2.1 Statistical Methods

The acoustic data collected during this study will be carefully analyzed both by inspection and use of appropriate statistical techniques to derive maximum information. Due to the size of the 1/3-octave band data, it will not be reduced with statistical analysis. However, a variety of statistical techniques will be performed with the A-weighted levels.

It is not expected that the statistical analysis will replace engineering evaluation of the data. The statistical evaluation will be designed to formally validate conclusions drawn by inspection of the data and point to conclusions that are not obvious from inspection of the data. It is anticipated that evaluation methods such as plots of noise level against speed or comparing different averages (i.e., the average of all attenuation values of one type of resilient wheel with another type of resilient wheel) will be used.

To illustrate the type of statistical analysis that may be performed, the data in Table 5-1 has been analyzed using least squares to determine best fit lines, and analysis of variance (ANOVA) to evaluate a linear model of the data. The data given in Table 5-1 is typical of data that will be collected. It involves two types of transit cars, four rail conditions and three speeds with two passbys at each speed and represents actual data obtained at a transit facility.

Least squares and analysis of variance are not the only statistical techniques that may be used in the final analysis of the data collected in this study. It is to be expected that inspection of the measurement results will indicate the appropriate tests for the specific data.

One technique that will be used whenever possible is blocking. Blocking could be important in this series of tests, particularly if weather conditions have a measurable influence on the A-weighted noise levels. The weather conditions for each test phase can be expected to be fairly constant, although weather conditions may vary significantly between test phases. Hence, wherever possible, the test design proposed will take advantage of blocking to reduce experimental variance due to the time lapse between phases.

5.2.1.1 Least-Squares Analysis - The basic purpose of least squares analysis is to determine the line best fitted to a set of data using a specific mathematical model. In this study, the noise level (L) as a function of speed (V) will be characterized by the model:

$$L = A \log V + B, \qquad [5\text{-}1]$$

where L is the noise level as a function of speed, V is speed, and A and B are constants determined from the data.

In addition, the standard deviation of the random errors about the least squares line will be estimated using:

$$s^2 = \frac{\sum_{i=1}^{n} (\hat{L}_i - L_i)^2}{n - 2}, \qquad [5\text{-}2]$$

where $\hat{L}_i$ is the least squares predicted noise level at speed V_i, L_i is the observed noise level at speed V_i, and n is the number of observations. The estimator of the standard deviation, s, can then be used to construct confidence intervals for the constants A and B and for any predicted noise level, L_i.

Figure 5-1 is a plot of the sample data showing the data points and the best fit lines. The data points are generally within ±1 dBA of the least squares line.

The data has been reduced further by calculating the average noise level values for each car and rail combination. Although the average values have been calculated using the method outlined in paragraph 3.3, a straight arithmetic average of the measured values would not be substantially different. Tables 5-2 and 5-3 summarize the average values and the slopes with their respective confidence intervals as determined by the least squares analysis.

TABLE 5-1. SAMPLE A-WEIGHTED PASSBY DATA (dBA)

Speed (mph)	Car A				Car B			
	Rail Type				Rail Type			
	1	2	3	4	1	2	3	4
30...	72.0	79.0	76.0	86.0	80.0	81.5	76.0	84.5
30...	72.0	78.5	76.0	84.5	78.0	82.0	78.0	83.5
40...	77.5	83.0	81.0	89.0	82.0	86.0	84.0	88.0
40...	76.0	82.0	80.5	90.5	84.0	87.5	83.0	89.0
50...	79.0	84.0	85.0	92.5	86.0	89.5	88.0	92.0
50...	81.0	86.0	84.0	94.0	87.0	89.0	88.0	92.0

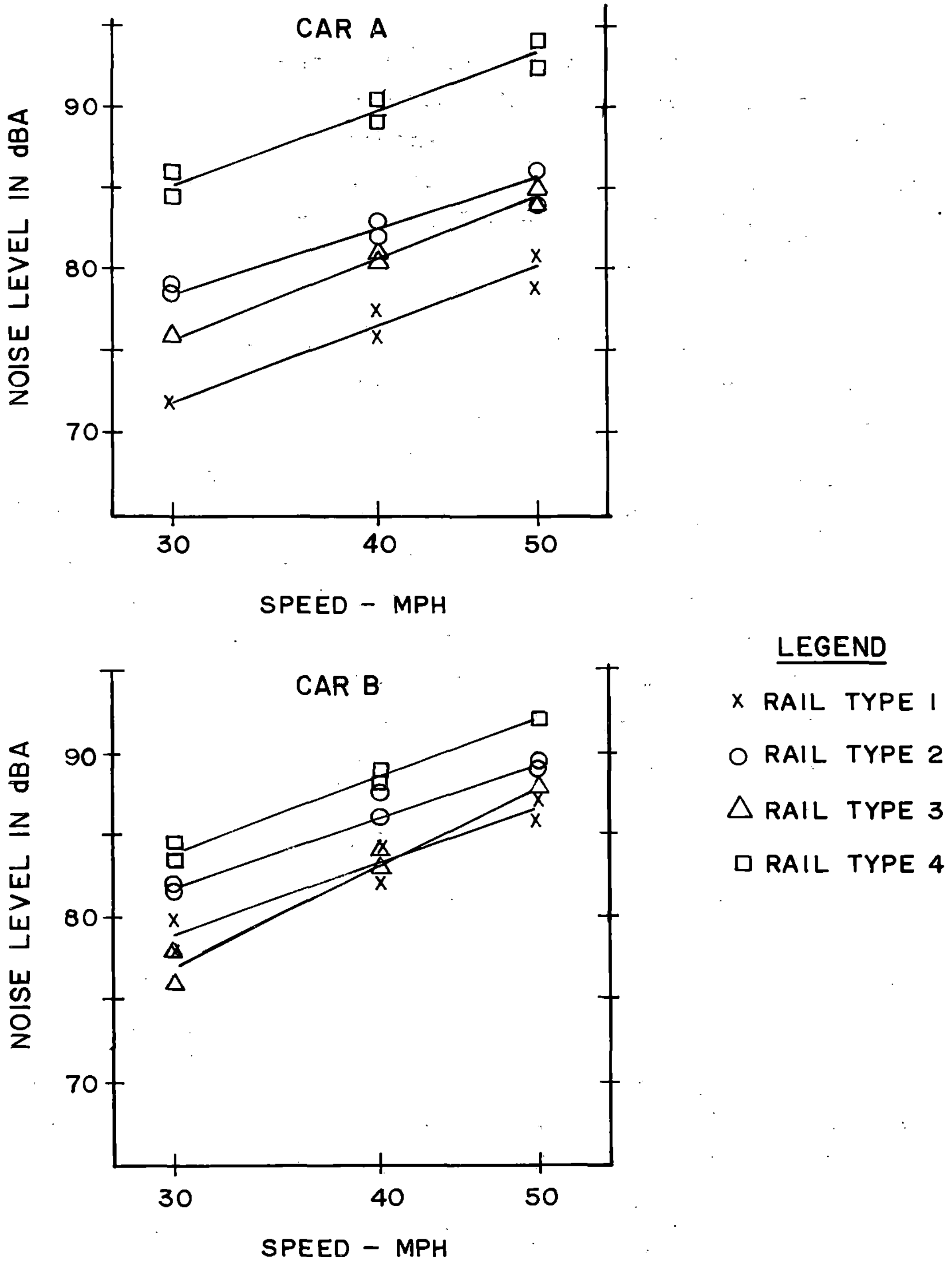

Figure 5-1 Sample A-Weighted Passby Data Plotted as Function of Speed

TABLE 5-2. SUMMARY OF A-WEIGHTED NOISE LEVELS AVERAGED* OVER SPEED (dBA)

Car Type	Rail Type			
	1	2	3	4
A..........	74.0	80.3	78.0	87.1
B..........	80.7	83.8	79.7	85.9

*Average used is the integrated average of least square lines over the speed range of from 30 to 50 mph.

TABLE 5-3. SUMMARY OF SLOPES AND 95-PERCENT CONFIDENCE INTERVALS DETERMINED USING METHODS OF LEAST SQUARES

Car Type	Rail Type			
	1	2	3	4
A......	36.1 ± 11.2	28.3 ± 10.2	38.3 ± 4.9	36.1 ± 11.5
B......	33.7 ± 13.3	34.1 ± 9.2	49.7 ± 10.1	36.1 ± 6.2

It is possible to further analyze this data in terms of the attenuation relative to a specific reference condition. First, assume that the Car A on Track 4 represents the "standard condition" for this set of data, and the data for Car A on Track 4 given in Table 5-1 represent all of the data taken for the reference condition. It is then possible to determine the "standard reference" levels using a least squares fit of the data from Car A on Track 4. The result is the reference levels given in Table 5-4 for the three speeds:

TABLE 5-4. SAMPLE REFERENCE LEVELS

Speed (mph)	Reference Level L_{REF} (dBA)
30........	85.2
40........	89.8
50........	92.3

As described in paragraph 3.3, the absolute A-weighted passby levels can be transformed to attenuation (relative to Car A on Track 4) values using the reference levels in Table 5-4 without increasing the variance of the data. The equation for the transformation is:

$$\Delta L_i = L_{REF} - L_i \, , \qquad [5\text{-}3]$$

where ΔL_i is the attenuation for observation i, and L_i is the observed noise level for i^{th} sample.

The attenuation levels are tabulated in Table 5-5. Note that the variations between car type and rail type are the same for either the absolute levels in Table 5-1 or the attenuation values in Table 5-5.

What has been altered is the speed relationship. Inspection of the attenuation values indicates that speed has some influence, although limited, on the attenuation between 30 mph and 50 mph. It would be possible to investigate the attenuation values in more detail using the least squares method to determine best fitted lines to the data.

TABLE 5-5. SAMPLE A-WEIGHTED PASSBY DATA FOR ATTENUATION* (dBA)

Speed (mph)	Car A Rail Type				Car B Rail Type			
	1	2	3	4	1	2	3	4
30...	13.2	6.2	9.2	-0.8	5.2	3.7	9.2	0.7
30...	13.2	6.7	9.2	0.7	7.2	3.2	7.2	1.7
40...	12.3	6.8	8.8	-0.8	7.8	3.8	5.8	1.8
40...	13.8	7.8	9.3	0.7	5.8	2.2	6.8	0.8
50...	14.2	9.2	8.2	0.7	7.2	3.7	5.2	1.2
50...	12.2	7.2	9.2	-0.8	6.2	4.2	5.2	1.2

*Attenuation is defined as $L = L_{REF} - L_A$. The levels of L_{REF} are derived from the observed levels of Car A on Track 4.

Inspection of these results reveals that rail type has a consistent influence on the slope of the least square lines, although car type does not have a consistent influence; sometimes the slope is higher for Car A and other times lower. It is also interesting to note that the average values over the speed range for Car A and Car B on the same rail type differ by only 1.2 to 3.5 dBA except on rail type 1 where the difference is 6.7 dBA. This comparison indicates that the physical differences between Car A and Car B result in the greatest differences in noise radiation on rail type 1. Hence, the implication is that substituting Car A for Car B would result in a substantial reduction of noise if the transit system used primarily rail type 1.

5.2.1.2 **Analysis of Variance** - The data from Tables 5-1 and 5-5 will be investigated using standard analysis of variance techniques, assuming a linear model of the data variation. The data will then be analyzed to determine which terms of the model are significantly different from non-zero.

The sample analysis is a standard three factor analysis of variance with two observations for each combination of factors. Tables 5-6 and 5-7 summarize the results of the analysis of variance. Shown in the tables are the sources of variation indicated by analysis of variance to be significant at the 0.01 level. The interpretation is that these sources of variation cause significantly more variation than can be explained as experimental error.

The general conclusion is that car type, rail type and speed along with the interaction of car type and rail type all have a significant influence on the noise level. The conclusion from Table 5-7 is that car type, rail type and car/rail interaction have an influence on attenuation; however, speed does not have an identifiable effect. Comparing Tables 5-6 and 5-7, it is evident that changing from absolute levels to attenuation influences the variance of the speed factor only, and does not influence any of the interaction effects. These results are expected in deriving attenuation from the absolute levels, since the same reference level is used for all measurements at the same speed.

It also is possible to contrast specific levels of the factors (i.e., rail type 1 compared to rail type 2). Such tests will help establish whether the data indicates that the differences between the observations at the different levels of the factor are significant. For example, contrasting the difference between the average of all observations on rail 1 and the average of observations on rail 2 will help indicate if rail 1 and rail 2 have different noise radiating characteristics.

TABLE 5-6. ANALYSIS OF VARIANCE FOR SAMPLE A-WEIGHTED PASSBY DATA (See Table 5-1)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio
Total..............	1327.0	47	----------	----------
Car Type...........	101.0	1	101.0	126.0*
Rail Type..........	569.0	3	190.0	238.0*
Speed..............	529.0	2	264.0	332.0*
INTERACTIONS				
Car/Rail...........	96.0	3	32.0	40.0*
Car/Speed..........	1.4	2	0.7	0.9
Rail/Speed.........	9.1	6	1.5	1.9
Car/Rail/Speed.....	3.2	6	0.5	0.7
Error..............	19.1	24	0.8	----------

*The indicated F Ratios are significant at the 0.01 level.

TABLE 5-7. ANALYSIS OF VARIANCE FOR ATTENUATION DATA (See Table 5-5)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio
Total..............	802.00	47	----------	---------
Car Type...........	100.00	1	100.00	125.0*
Rail Type..........	571.00	3	191.00	237.0*
Speed..............	0.16	2	0.08	0.1
INTERACTIONS				
Car/Rail...........	97.00	3	32.00	40.1*
Car/Speed..........	1.40	2	0.70	0.9
Rail/Speed.........	9.10	6	1.50	1.9
Car/Rail/Speed.....	3.30	6	0.60	0.7
Error..............	19.30	24	0.80	---------

*The indicated F Ratios are significant at the 0.01 level.

5.2.2 Dominance of Wheel-Rail Noise

When measuring the noise generated by the interaction of the wheels and the rails, it will not be possible to exclude extraneous noise sources. Other sources,such as motors and fans,will be a part of the total noise field. Fortunately, if it can be shown that if one noise source attains a substantially higher level than all of the rest, then the noise level measured will reflect the level of only the dominant source. That is, the level measured will be the same as that which would exist if all of the other sources were not present.

Since the total noise field will be measured in this study, but wheel-rail noise is of primary interest, it must be first determined that wheel-rail noise is the dominant source of wayside and interior noise. When establishing this dominance, it will be important to document the levels of the noise sources on the transit cars excluding wheel-rail noise to determine the maximum attenuation of wheel-rail noise that can be observed in this study. Tests with the transit cars on jacks will be performed to establish the wayside and interior noise levels with the car wheels freely rotating. A description of the steady noise level, L_A, will be used to measure these interior and exterior noise levels. The difference between the passby noise level and the level with the cars on jacks will establish the limits on the observable reduction of wheel-rail noise.

If the wayside noise is six to ten dBA higher than the level measured while the car is on jacks, then the wheel-rail noise is predominant. If it is only three dBA higher, then the wheel-rail noise is of similar magnitude to the other noise sources.

In addition to noise measurements, vibrational tests also will be conducted. One purpose of the vibration measurements is to guarantee that the noise heard during the passage of a train is predominantly created by the wheels and the rails. A series of tests using accelerometers attached to the wheels and rails will measure vibration levels simultaneously with measurements of the wayside noise for several passbys of trains with all steel wheels. Using the results of earlier theoretical studies of wheel-rail noise the wayside noise levels will be predicted from the vibration data.*

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* Kurzweil, L. G. et al, Noise Assessment and Abatement in Rapid Transit Systems, DOT Report No. UMTA-MA-06-0025-74-8, September 1974.

Comparison of the measured wayside noise levels and the predicted noise levels will help establish the amount which wheel-rail noise contributes to the wayside noise levels.

5.2.3 Wheel and Rail Roughness Tests

Wheel truing and rail grinding are two of the noise reduction techniques that will be investigated in this study. Acoustic measurements to document wheel and rail roughness will be made directly after the wheels have been trued and the rails have been ground, and also after the wheels and rails have been used in revenue service for a one year period. The correlation between the wheel and rail deterioration and the noise radiation will be investigated. In addition, the degree and rate of wear will be documented with interim measurements on the wheels and rails. The method that will be used to measure the wheel and rail roughness has not been fully determined at this time.

The correlation of the single number, overall measure of wheel-rail roughness, L_{RUF}, and the amount of time the wheels and rail have been in service will be investigated first. This will indicate the validity of L_{RUF} as a measure of the roughness. Following the verification of L_{RUF} as a valid measure of roughness, the length of time in service, number of car miles or number of passbys over a section of rail required to reach a specified degree of roughness will be investigated.

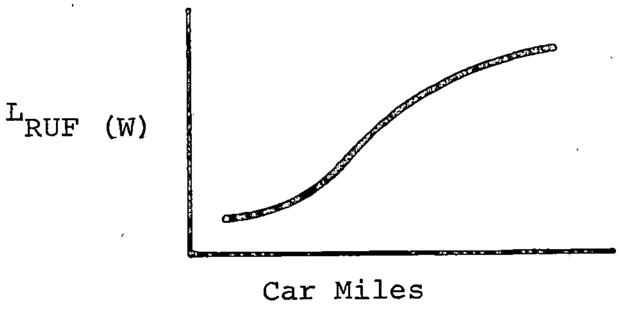
The primary use of L_{RUF} will be to evaluate the effectiveness of the wheel truing and rail grinding and to help establish schedules of wheel truing and rail grinding necessary to maintain acceptable noise levels. This information will allow a transit system to schedule its maintenance to prevent wheels and rails from producing excessive noise.

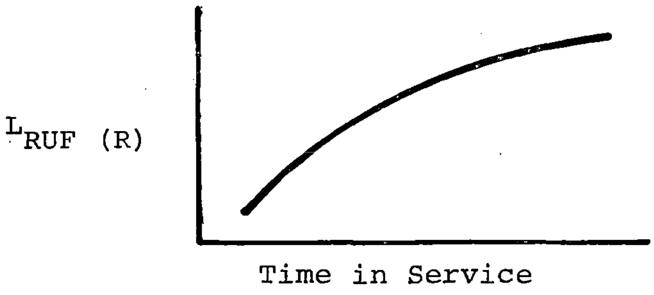
Implicit in this discussion is the assumption that the overall measure of wheel and rail roughness, L_{RUF}, will correlate with the wheel-rail noise levels. It is expected, based on the results of previous theoretical work in this series of studies, that for the tangent welded track a relationship between noise level and L_{RUF} at specific speeds and for specific types of wheels can be established. The form of the relation is expected to be:

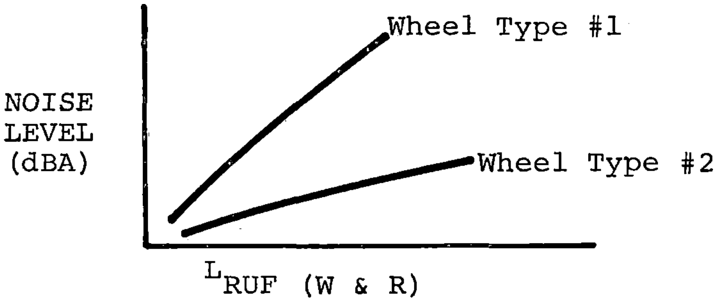
$$L(V) = L_{RUF}(V) + C, \qquad [5\text{-}4]$$

where C is a constant, and $L(V)$ is the noise level as a function of speed. $L_{RUF}(V)$ is the roughness measure as a function of speed. Whether or not this is an appropriate form for the relationship between speed and roughness will be investigated once the data is available. It may be that a relationship of the form given above will be valid for the 1/3-octave band data only.

To simplify the roughness data, it is expected that graphs of the following general form will be presented. Whether the data will be presented in exactly this form depends on the results of the roughness measurements. The subscripts in parentheses refer to the roughness of the wheel (W) or the rail (R).







5.2.4 Proposed Evaluation Methodology

The methodologies proposed for evaluation of acoustical data for each specific track type; the quantities that will be varied in the testing on the track section; and some of the specific questions the evaluation will be designed to answer are summarized below.

A control track section will be included at three of the test tracks (surface curve, and elevated tangent jointed and welded). The control track sections will be worn prior to the start of the testing phases and will be unchanged (except for normal wear) during the entire study. On these test tracks, each measurement taken on the experimental track sections will be repeated on the adjacent control track section.

The type of information that will be provided by the control track measurements are:

1) Identification of anomalous data.
2) Improved estimates of normal variability.
3) Indication of results for wear periods of longer than one year.
4) Direct comparisons of the differences between ground and worn rail for the various wheel types and conditions, and at various speeds.

The proposed statistical design will take every possible advantage of blocking to reduce variability due to such uncontrolled factors as wind, speed, and humidity. The data from the control track sections also will be useful in the evaluation of blocking.

In addition to the measurements outlined for each test track section, measurements under the following conditions also will be taken:

a) Two-car train with pre-worn wheels giving data on wear periods longer than one year.
b) Revenue service trains to help determine the manner in which the test data should be related to normal length trains with passenger loads.
c) Single car trains to investigate the relationship between the noise generated by single-car and two-car trains.
d) Wayside measurements at a distance farther from the track than the normal wayside measurements to aid in evaluating the effect of distance from the track.

5.2.4.1 Tangent-Welded Track (Elevated) -

Measurement Conditions -

Locations: interior, wayside

Speeds: 40, 60, 80 Km/h (two samples at each speed)

Track Conditions: ground, worn

Wheels: five types

Wheel Conditions: new, worn, trued (three wheel types).

This test track will contain a control track section. L(V) and L_{AV} are the parameters that will be evaluated. As previously described in Section 3, L(V) defines the A-weighted noise level as a function of speed and L_{AV} is a single number which indicates an average noise level for the speed range measured.

At each of the three specified speeds,two train passbys will be recorded, i.e., a total of six measurements for each wheel and track configuration. Experience has shown that the variation between two train passbys of the same train, at the same speed on the same track, and on the same day is generally less than one dBA. Since a change in sound level of one dBA is barely perceptible to the human ear, two train passbys are sufficient to get an accurate measure of the noise level of the train. Statistical analysis will be used to quantify the variance in noise level. The use of the control track section ensures that variables, such as weather, will not go unnoticed. Any variability in train speed, that is if the train speed is 48 mph instead of 50 mph, will be taken into consideration in the calculation of L(V) and L_{AV}.

The least squares best fit lines for each set of data will be generated and the variations of the lines and the slopes of lines will be evaluated using the procedures as outlined in paragraph 5.2.1.

The attenuation values will be evaluated using analysis of variance (ANOVA) procedures designed to answer the following questions for the tangent welded track on elevated structure:

1) Is there a significant difference between the experimental track section and the control track section?
2) Is there a significant difference between new and trued wheels?
3) What is the difference between new and worn wheels?
4) What is the difference between worn and ground track?
5) How do wheel and rail conditions interact?
6) What are the primary effects of wheel type?
7) For 3, 4 and 5, what is the interaction with wheel type?
8) Over the measured speed range, does speed have any identifiable influence on attenuation?
9) Does speed interact with 2 through 7 above?

All of the above questions will be evaluated for both the interior and wayside measurements. In addition, the difference between interior attenuation and wayside attenuation will be investigated.

5.2.4.2 Tangent-Jointed Track (Elevated) -

Measurement Conditions -

Locations: interior, wayside

Speeds: 40, 60, 80 Km/h (two samples at each speed)

Track Conditions: worn,aligned, ground, aligned and ground

Wheels: five types

Wheel Conditions: new,worn, trued (three wheel types).

A control track section will be included at this test track.

The analysis of tangent jointed track is similar to that for the tangent welded track with a few exceptions. For tangent jointed rails, the discontinuities at the rail joints are generally larger than the roughness on the wheels and rails, and are a significant source of wheel-rail noise. When a wheel crosses a rail joint, an impact force is generated, and the peak noise created is of very short duration. The energy average noise level for the passby plateau, L_A, may not be strongly influenced by this peak noise level. Hence, it is conceivable that the peak noise level, or the impulsive noise level may be reduced by one of the noise control treatments while L_A is not reduced. In such a case, the annoyance potential of the noise may be reduced, even though the reduction is not reflected in L_A. Hence, in the reduction of the passby noise data, a measure of the impulse noise, L_{IMP}, also will be found. If the attenuation in L_{IMP} is effectively the same as found for L_A, there will be no need to analyze L_{IMP} further. However, if L_{IMP} indicates that L_A does not adequately represent the noise attenuation, further investigation may be necessary.

Another factor that differentiates the tangent jointed from tangent welded data is that the tangent jointed test track will have two experimental track sections along with a control section. The extra sections will allow investigation of the following track conditions:

1) Worn track.
2) Track with rail joints aligned to reduce impact noise at rail joints.
3) Track with the rails ground smooth but the joints unaligned.
4) Track with the rails both ground smooth and the joints aligned.

In the same manner as the analysis of the tangent welded data, least squares best fit lines will be evaluated for each set of data. The variations between the lines and the slopes of the lines also will be evaluated.

The ANOVA of the attenuation values will be designed to provide answers to the same general questions outlined in paragraph 5.2.4.1 for tangent welded track.

5.2.4.3 Short-Radius Curve (At Grade) -

Measurement Conditions -

Locations: interior, wayside

Speeds: normal operating speed only (six samples)

Track Conditions: ground, worn

Wheels: five types

Wheel Conditions: new, worn, trued (three wheel types).

A control track section will be included on this test track. Since there is only a limited range of possible speeds on short radius curves, all the samples will be taken at the normal operating speed on the curve. Hence, there will be no need to fit the data to least squares lines. Instead the average values for the different conditions can be compared directly using a standard Student's t-test. The wheel squeal noise produced on curves is a phenomenon that differs substantially from the roar or impact noise typical of tangent track. Due to the specific characteristics of wheel squeal noise, the measure used to evaluate wheel squeal requires further discussion. It is to be expected that the wheel squeal noise will be more variable than tangent track noise. Due to the expected fluctuation, there is a chance that the final methodology used to analyze the level of wheel squeal will change once the data is available. Hence, the methodology given below must be considered tentative.

There are two basic manners in which wheel squeal can be evaluated. The first is to simply read from a strip chart the peak levels of squeal while the train is traversing the test curve. The second is to derive an average level of the noise while the train rides the curve, for example, using a real time analyzer. The energy average noise level is expected to give the most consistent results and to correspond best with the subjective human evaluation of the squeal noise. However, based on previous measurements it is expected that this average level, L_A, will vary as much as ± three dBA between runs of the same train over the same track. Six runs will be sufficient to generate a valid mean noise level, L_{AV}. All six runs will be at the same operating speed. As in all the tests, a relative measure, ΔL_{AV}, will be derived using the relation:

$$\Delta L_{AV} = L_{AV} - L_{REF} , \qquad [5-5]$$

where L_{REF} is the measured L_{AV} for a curve with worn rail and a train with worn standard steel wheels.

ANOVA tests will be designed to answer the following questions:

1) Is there a significant difference between the experimental track section and the control track section?
2) Is there a significant difference between new and trued wheels?
3) What is the difference between new and worn wheels?
4) What is the difference between worn and ground track?

5) How do wheel and rail conditions interact?

6) What is the overall variance of wheel squeal noise?

7) What are the primary effects of wheel type?

8) How does wheel type interact with 3, 4 and 5 above?

The above questions will be evaluated for both the interior and the wayside measurements. ANOVA will be used to evaluate the relationship between the interior attenuation and the wayside attenuation.

5.2.4.4 Short-Radius Curve (Subway) -

Measurement Conditions -

Location: interior

Speeds: normal operating speed only (six samples)

Track Conditions: ground, worn

Wheels: five types

Wheel Conditions: new, worn.

There will not be a control track section on this test track. Only interior measurements will be taken. The analysis of the interior measurements will be the same as outlined in paragraph 5.2.4.3, the short radius curve (at grade). In addition to the relevant questions outlined in paragraph 5.2.4.3, the statistical analysis also will investigate the relationship between attenuation results on short radius curves in subways and at grade.

5.2.4.5 Tangent-Welded (Subway) -

Measurement Conditions -

Location: interior

Speeds: three (two samples at each speed)

Track Conditions: ground, worn

Wheels: five types

Wheel Conditions: new, worn.

There will be no control track section on this test track. Only car interior measurements will be made in the subway. The analysis of the interior measurements will be the same as used on tangent-welded (elevated) test track data. In addition to the relevant questions outlined in paragraph 5.2.4.1, analysis also will be done to determine if there are any significant differences between the attenuation results on tangent-welded track in subway tunnels and on elevated structure.

5.2.4.6 Tangent-Jointed (Subway) -

Measurement Conditions -

Location: interior

Speeds: three (two samples at each speed)

Track Conditions: worn, ground and aligned

Wheels: five types

Wheel Conditions: new, worn.

There will be no control track section on this test track, and only interior measurements will be taken. The analysis of the data will be the same as outlined for tangent-jointed (elevated). In addition to the relevant questions outlined in paragraph 5.2.4.2, the statistical analysis also will investigate the differences between the attenuation results on jointed track in subway and on elevated structure.

5.2.4.7 Station (Subway - Welded Track) -

Measurement Conditions -

Location: inside station

Speeds: Stop, skip-stop (three of each at normal speeds)

Track Conditions: worn, ground

Wheels: five types

Wheel Conditions: new, worn.

L_E, a measure of the total acoustic energy of a train passby, will be used to evaluate the station noise. A normalizing factor may be incorporated into L_E to give numerical values which will be approximately equal to the energy average noise level during the train passby.

The differences between the absolute levels of L_E for the various measurement conditions will be compared using Student's t-tests.

Using analysis of variance (ANOVA) the effects and interactions of the various measurement conditions on the attenuation of L_E will be investigated. Some of the questions the ANOVA will be designed to answer are:

1) What is the influence of wheel condition?

2) What is the influence of rail condition?

3) What is the interaction between 1 and 2?

4) What is the primary effect of wheel type?

5) What is the interaction of wheel type with 1, 2 and 3?

6) Is there a significant difference between the attenuation for normal train stops in the station and skip-stop passes through the station?

7) How do the results compare to the measurements made on tangent welded track on elevated structure and in the subway tunnel?

5.2.4.8 Station (Subway - Jointed Track) -

Measurement Conditions -

Location: on station platform

Speeds: stop, skip-stop (three each at normal speeds)

Track Conditions: worn, ground and aligned

Wheels: five types

Wheel Conditions: new, worn.

The same measurements and analysis will be performed as for the subway station with welded track summarized in paragraph 5.2.4.7.

5.2.4.9 Station (Elevated - Jointed Track) -

Measurement Conditions -

Location: inside station

Speeds: stop and skip-stop (three each at normal speeds)

Track Conditions: worn, or as is

Wheels: one type

Wheel Condition: new.

These tests will merely give enough information to allow extrapolation using the data from other test tracks.

5.2.4.10 Frog -

Measurement Conditions -

Locations: interior, wayside

Speeds: 40, 60, 80 Km/h (two passbys at each)

Track Conditions: as is

Wheels: five types

Wheel Conditions: new.

For the interior and wayside data, the least squares fit lines of L_A as a function of speed will be generated for each wheel type. The variations between the lines and the slopes will then be evaluated. In addition, ANOVA tests will be performed to evaluate the influence of the various conditions on L_A.

Since impulsive noise is a very important component of noise at a rail frog, the influence of wheel type and speed on L_{IMP} also will be evaluated. In addition, the correlation between the attenuation of L_A and the attenuation of L_{IMP} will be evaluated.

The primary questions the ANOVA tests will be designed to answer for both the attenuation of L_A and L_{IMP} are:

1) What is the effect of wheel type?
2) What is the influence of speed?
3) Can interaction effects between wheel type and speed be identified?
4) How well do the attenuation of L_{IMP} and L_A compare?
5) How well do the interior and wayside measurements correlate?

5.3 COST ANALYSIS

The cost data collected during the study will be evaluated and unit costs for the previously defined cost parameters developed. The unit costs will be used to finalize the method for determining optimum allocation of resources among the four noise reduction techniques under study.

5.3.1 Analysis of Non-Acoustic Data

Data acquired from other systems and manufacturers will be evaluated to determine factors potentially affecting the transferability of rail grinding costs and cycle projections to other systems.

The transferability of wheel truing costs and cycle projections to rail transit systems with varying system operating conditions, car design and maintenance equipment available also will be assessed.

In addition, the data collected from surveys of transit systems on the qualitative parameters (listed in paragraph 3.6) will be used to evaluate the following questions:

1) Do the qualitative parameters have any influence on the transferability of the results of this study to other transit systems?

2) Is there any potential influence of the qualitative parameters on the practicality of applying any of the four noise control methods to other transit systems?

Data acquired concerning the rate of growth of rail irregularity versus total car miles or passes operated over a section of track will be evaluated relative to measured increases in noise level for a comparable period to estimate rail grinding cycles required to maintain optimal noise level. Rail grinding cycles, as a function of car passes, will be a direct input into the determination of system life cycle costs.

The rate of growth of wheel roughness versus car miles will be evaluated relative to measured increases in noise level reduction attributable to wheel truing to estimate wheel truing cycles required to maintain optimal noise levels. It is anticipated that the phasing of the test measurements will enable the relative noise reduction effectiveness of wheel truing as well as rail grinding to be independently ascertained. The projected wheel truing cycles, as a function of car miles, will be a direct input into the determination of system life cycle costs for wheel-rail noise control.

5.3.2 Total Costs

For each of the cost parameters (X_1 through X_{17}) described in paragraph 3.4, values will be determined quantitatively for developing the total costs associated with each of the noise control techniques.

Specifically, the values will satisfy the following questions:

1) What is the total initial direct cost of a wheel truing machine?

2) What is the total initial direct cost of a rail grinding machine?

3) What is the total initial direct cost per car of resilient wheels?

4) What is the total initial direct cost per car of damped wheels?

5) What is the total cost per car of truing wheels?

6) What is the total cost of inspecting resilient wheels per car?

7) What is the total cost of inspecting damped wheels per car?

8) What is the total cost of grinding rail per mile?

9) What is the total cost of replacing tire and resilient unit per car?

10) What is the total cost of replacing wheel damping per car?

11) What is the total cost of replacing steel wheels per car?

12) What is the total cost of inspecting steel wheels per car?

13) What is the residual value of a wheel truing machine?

14) What is the value of a rail grinding machine at the end of its useful life for use in residual value calculation?

15) What is the residual value per car of resilient inserts and tires at the end of their useful life?

16) What is the residual value per car of wheel damping materials at the end of their useful life?

17) What is the residual value of a steel wheel at the end of its useful life?

5.3.3 Method of Life-Cycle Cost and Maximum Benefit Analysis

The total cost for each noise control technique will have numerous components, all of which are sensitive to a variety of factors including: discounting (present value of cash flow), system life, wheel life, maintenance cycles, the accuracy of material and labor cost estimates, system conditions, the transferability of data. A method to examine logical combinations of resilient wheel, wheel damping, wheel truing, rail grinding, cost components, budget levels, and sensitivity factors will be developed to determine minimum life cycle costs. The life cycle costs for wheel-rail noise control will encompass the initial costs and maintenance costs for the projected system life analyzed.

The total cost associated with maintaining wheels and rails or providing alternative wheel systems for a particular rail rapid transit system will vary with the specified noise limit and local characteristics of that system.

The acoustic and cost data developed will be combined into a method for defining the requirements for implementing noise level reductions. A general description of the method as it would be applied to a specific system follows. It has been developed as an extension of preliminary work performed by the TSC in previous reports on noise reduction costing.*

5.3.4 Array of Events

In addition to the four noise control techniques to be investigated, the cost of maintaining standard steel wheels must be considered as a base case and as a part of the total cost of maintaining a system without the installation of resilient or damped wheels. The techniques and associated costs are defined in Table 5-8.

Each of the wheel types is considered mutually exclusive of the others.

The array of techniques to be evaluated are defined in Table 5-9.

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* Kurzweil, L. G., et al, Noise Assessment and Abatement in Rapid Transit Systems, Report on the MBTA Pilot Study, Report No. UMTA-MA-06-0025-74-8, September 1974.

TABLE 5-8. NOISE CONTROL TECHNIQUES AND ASSOCIATED COSTS

Symbol	Noise Control Technique	Costs
A_i....	Install resilient wheel type i..	$X_3 + X_6 + X_9 - X_{15}$
B.....	Install damped wheels..........	$X_4 + X_7 + X_{10} - X_{16}$
C....	True wheels....................	$X_1 + X_5 - X_{13}$
D....	Grind rail.....................	$X_2 + X_8 - X_{14}$
E....	Retain steel wheels (status quo)	$X_{11} + X_{12} - X_{17}$

The general outline of the tentative methodology for applying the data developed follows:

1) Estimate the noise level at standard receiver locations. Group track segments with similar construction and operating characteristics as well as similar noise levels into scenarios.

2) From data on noise control technology, determine potential noise source reduction with each array for each track element. Combine the reductions into a consolidated reduction for both patrons and wayside.

    a) Combine patron and wayside reduction into a single number consolidated reduction

    b) Identify installation and maintenance costs.

3) Compute the costs and noise reductions achievable by application of each array and combine into system cost, so as to satisfy the following objectives:

TABLE 5-9. TECHNIQUE ARRAYS

Array	Combination of Techniques
Install resilient wheels..................	A_i
Install resilient wheels, true wheels at a given interval...........................	$A_i + C$
Install resilient wheels, grind rail at a given interval...........................	$A_i + D$
Install resilient wheels, grind rail and true wheels at given interval............	$A_i + C + D$
Install wheel damping material on standard wheels..........................	B
Install wheel damping material on standard wheels, true wheels at given interval.....	B + C
Install wheel damping material on standard wheels, grind rail at given interval......	B + D
Install wheel damping material on standard wheels, true wheels, and grind rail at given interval............................	B + C + D
Retain steel wheels......................	E
Retain steel wheels, true wheels at given interval.................................	E + C
Retain steel wheels, grind rail at given interval.................................	E + D
Retain steel wheels, true wheels and grind rail at given interval.............	E + C + D

a) Determine the least costly combination of techniques for achieving a specified noise limit

b) Determine the combination of techniques to result in the greatest benefit for any given budget.

Clearly the first step will be to divide the system into separate components. The primary categories would be:

a) Welded surface or elevated track

b) Jointed surface or elevated track

c) Welded subway

d) Jointed subway

e) Curves with squeal - elevated or surface

f) Curves with squeal - subway

g) Station with welded track - elevated or surface

h) Station with jointed track - elevated or surface

i) Station with welded track - subway

j) Station with jointed track - subway

k) Frogs and other isolated impact areas.

The different primary categories would then be classified according to noise level groupings, e.g. 95-91 dBA, 90-86 dBA, etc. Data on anticipated noise levels for each rail rapid transit system will not be developed during this study.

5.3.5 Procedure

5.3.5.1 Total Cost for Achieving Specified Noise Limit - The procedure will include all costs associated with a given technique, and will depend upon the length of track being treated, the number of cars being treated and the period of time considered for analysis purposes.

In addition, the frequency of the performance of the various maintenance and or replacement procedures will directly affect the cost effectiveness of each technique evaluated.

The costs associated with each technique or combination of techniques are sensitive to one or more of a variety of factors, i.e., discounting (present value of cash flow), system life, wheel life, maintenance cycles, the accuracy of material and labor cost estimates, system conditions and the transferability of data.

Life-cycle cost analysis is the procedure that will be utilized. For each technique, initial cost, maintenance costs, replacement costs, residual values (as required), and appropriate performance cycles will be developed.

The present value of all items will be calculated according to:

$$PV = \frac{A}{(1 + i)^{(t)}}, \qquad [5\text{-}6]$$

where PV is the present value of A dollars t years from now at a constant interest rate i, generally assumed to be 10%.

The result will be the unit total cost for life cycle (X) of:

1) Resilient wheels - A_i.
2) Damped wheels - B.
3) Wheel truing - C.
4) Rail grinding - D.
5) Standard steel wheels - E (for comparative purposes).

The method will permit the examination of logical combinations of resilient wheels, wheel damping, wheel truing and rail grinding to determine cost effective measures of achieving desired noise level reductions. It will include the present value of parameters previously described, as appropriate for each technique.

Calculated costs will be applied to a methodology for application to any rail rapid transit system in the United States.

5.3.5.2 Maximum Benefit for Given Budget - Whereas in the first analysis the noise reduction cost was unknown, for this series of calculations the cost is the known. The maximum benefit attainable by a noise control program is the unknown quantity.

The analysis procedure established must calculate the annual budgetary requirements as well as the cost effectiveness of the various possible noise reduction programs.

Life cycle costing will be used to evaluate cost effectiveness while annual cost calculations will determine budgetary expenditures.

Since the costs associated with rail grinding, wheel truing and wheel maintenance are generally contained in the individual budgets of the maintenance of way and car equipment departments, respectively, a simplifying assumption will be an all encompassing noise abatement budget.

The analysis procedure will permit the examination of logical combinations of resilient wheels, wheel damping, wheel truing and rail grinding to determine the optimum distribution of the system budget to the individual departments.

5.3.5.3 Life-Cycle Cost Equations - Life-cycle cost equations for an assumed 20 year life cycle and a 10% interest rate are listed below:

1) Resilient wheels,

$$\text{Life-Cycle Cost} = PV = X_3 + \sum_{t=1}^{t=20} \frac{X_6}{(1+.10)^t}$$

$$+ \frac{X_9}{(1+.10)^{20}} - \frac{X_{15}}{(1+.10)^{20}} \quad . \qquad [5\text{-}7]$$

2) Wheel damping,

$$PV = X_4 + \sum_{t=1}^{t=20} \frac{X_7}{(1+.10)^t} + \frac{X_{10}}{(1+.10)^{10}} - \frac{X_{16}}{(1+.10)^{10}}$$

$$+ \frac{X_{14}}{(1+.10)^{20}} - \frac{X_{16}+X_{17}}{(1+.10)^{20}} \quad . \qquad [5\text{-}8]$$

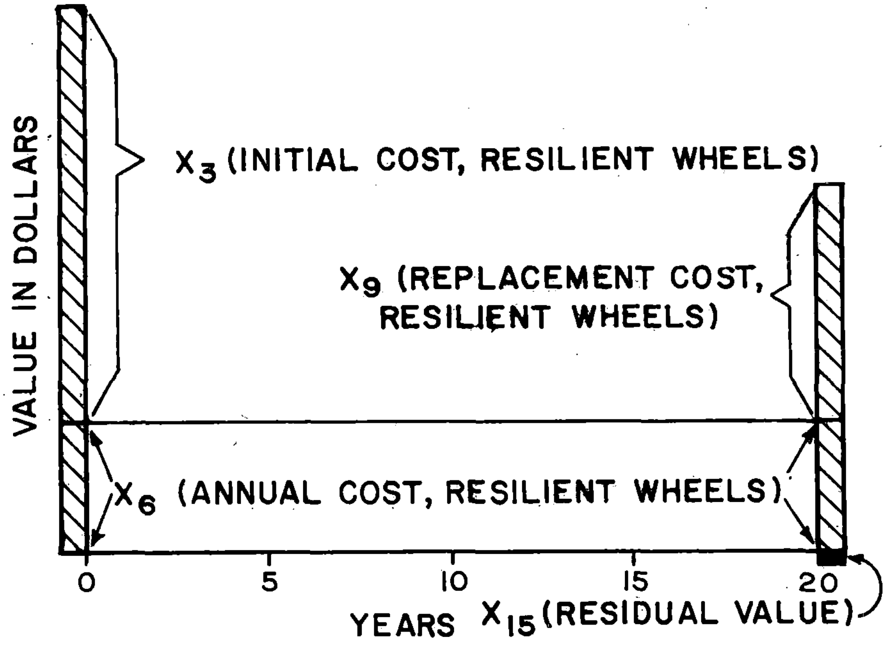
3) Wheel truing,

$$PV = X_1 + \sum_{t=1}^{t=20} \frac{X_5}{(1+.10)^t} - \frac{X_{13}}{(1+.10)^t} \quad . \qquad [5\text{-}9]$$

4) Rail grinding

$$PV = X_2 + \sum_{t=1}^{t=20} \frac{X_8}{(1 + .10)^t} - \frac{X_{14}}{(1 + .10)^{20}} \cdot \qquad [5\text{-}10]$$

Figure 5-2 is a graphic representation of the life cycle costs for Resilient Wheel A_i. The use of equation [5-6] will enable all costs to be reduced to 1976 dollars. All costs are one time costs, except for X_6, which is an annual cost.



20-YEAR ASSUMED LIFE-CYCLE

Figure 5-2 Twenty-Year Life-Cycle Costs Resilient Wheels

6. PRESENTATION OF RESULTS

6.1 FORMAT

The format to present the results of this study is designed to satisfy the program objectives outlined in Section 2. Basically, two separate sets of data (acoustic and cost) will be developed and ultimately combined into a cost versus benefit analysis. As the data to be presented for each of these parts are to some degree independent, the format that will be used to present each is outlined below.

6.2 ACOUSTICAL DATA PRESENTATION

Since it is expected that there will be an enormous quantity of acoustical data, even after the data has been reduced to its simplest form, a primary objective will be to provide a simple, straightforward presentation of only the most pertinent information in the body of the final report. The details concerning the results of specific passbys, the 1/3-octave band data, etc., will be placed in appendices. Although it is important to provide documentation of these results, removing them from the body of the report can considerably improve its flow and clarity.

The results for each test track section will be presented separately. However since the same type of data presentation will be used for each of the test track sections, there is no need to describe here the presentation for each track separately. The data to be presented for the tangent welded (elevated) test track are outlined below and are representative of the other test track sections:

1) Tables of average attenuation for various wheel and rail conditions (average level referred to a standard reference level) for both interior and wayside measurement locations. Table 6-1 is a sample of the type of table of average attenuation that will be presented.

2) Typical plots of L(V) level as a function of speed for interior and wayside measurement locations.

TABLE 6-1. SAMPLE OF AVERAGE ATTENUATION (dBA) FOR THE VARIOUS TRACK AND WHEEL CONDITIONS AVERAGE ATTENUATION FOR TANGENT-WELDED TRACK (ELEVATED)

Wheel Type	Condition	Rail Condition		
		Ground Smooth	Worn 1 Year	Worn 2 Years
Standard 1...	New..........	2	1	0
Standard 1...	1-Year Wear..	1	0	+1
Standard 1...	Trued........	2	1	0
Standard 2...	1-Year Wear..	1	0	+1
Standard 2...	2-Year Wear..	2	1	0
Resilient 1..	New..........	10	6	4
Resilient 1..	1-Year Wear..	8	5	3
Resilient 1..	Trued........	9	5	4

3) A summary of the conclusions that can be drawn from the least squares straight line fits of the A-weighted levels as a function of speed.

4) Sample plots of $\Delta L(V)$ (attenuation as a function of speed).

5) Representative 1/3-octave band data along with a discussion of conclusions that can be drawn from the 1/3-octave band data.

6) Representative A-weighted time histories of the train passbys.

7) A summary of the results of the statistical analysis, specifically the analysis of variance of the attenuation.

8) A discussion of the conclusions that can be drawn from the statistical analysis.

9) A discussion of the comparison and correlation of the results from the tangent-welded (elevated) test track with the results from other test tracks.

In addition to the specific measurement results at the various test tracks, the following general points will be covered in the text accompanying the presentation of data:

a) The differences in performance among the various types of wheels.

b) General summary of the error and statistical analysis results, particularly with reference to the repeatability of the results.

c) The influence of noise sources other than wheel-rail noise.

d) The correlation between the profilometer measurements and the noise radiation.

6.3 COST PRESENTATION

6.3.1 Unit Costs

The unit costs required for calculation of the initial direct costs, annual operating and maintenance costs and residual values for any urban rail system will be presented in an appropriate format. They will be based on an analysis of SEPTA costs acquired during the study, and the data from the survey of other systems and manufacturers.

6.3.2 Total Costs

Utilizing the cost data developed, curves will be plotted indicating the total cost for each of the techniques for systems of various sizes, i.e., rail grinding vs. number of miles of track to be ground for each year (Figure 6-1); wheel truing vs. number of cars to be trued each year (Figure 6-2); and cost of resilient wheels vs. number of cars in system (Figure 6-3). Rail transit system management, having calculated the various cycles for their system, will be able to develop the total annual cost for a particular array, knowing the noise reduction achievable through the use of that technique.

It is anticipated, for example, that the number of cars per year to be trued on a given system can be calculated using a procedure similar to that listed below:

6.3.2.1 Wheel Truing -

1) Total Car Fleet = K.

2) Average Annual Car Miles = CM (Miles/Car-Year).

3) Proposed Truing Mileage (Miles) = TMP.

4) Proposed Truing Cycle (Years/Car) = $\frac{\text{TMP}}{\text{CM}}$ = Ƶ.

5) Proposed Cars Trued/Year = K/Ƶ = K_t.

Knowing the number of cars to be trued annually, the rail transit system can determine the total cost of truing wheels by using a chart similar to Figure 6-1.

Similarly, the rail miles to be ground per year can be calculated as shown below.

6.3.2.2 Rail Grinding

1) Average Traffic (Annual Car Miles) = ACM

2) Total System Track Miles (Miles) = SM.

3) Proposed Grinding Cycle (Car Miles) = TCM.

4) Proposed Grinding Cycle (Years) = $\frac{TCM}{ACM}$ = GY.

5) Roughness Removed Per Pass = RP.

6) Estimated Roughness at TCM = R.

7) Passes Required = P = $\frac{R}{RP}$.

8) Productivity Per Hour = 3 mph.

9) Miles/Year to be Ground = $\frac{SM}{GY} = M_g$.

10) Annual Pass Miles = $P \times M_g$ = APM.

Knowing the number of miles to be ground per year, the total cost of grinding rail can be determined through the use of a chart similar to Figure 6-2.

6.3.2.3. Resilient Wheels - The calculation of the total cost of resilient or damped wheels will include estimating the expected useful life of the wheels on a particular system and the anticipated inspection schedules as well as knowing the number of wheels to be purchased. The necessary information can be calculated as follows:

1) Expected Life (Miles) = RM.

2) Average Annual Car Miles = CM.

3) Expected Life (Years) = $\frac{RM}{CM}$ = RY.

(i.e., must be replaced after 'RY' years)

4) Inspection Schedule (Years) = IY.

5) Annual Inspections = K(IY).

Knowing the number of wheels to be purchased, the expected life and the inspection cycle, the total cost of resilient wheels can be determined through the use of a chart similar to Figure 6-3.

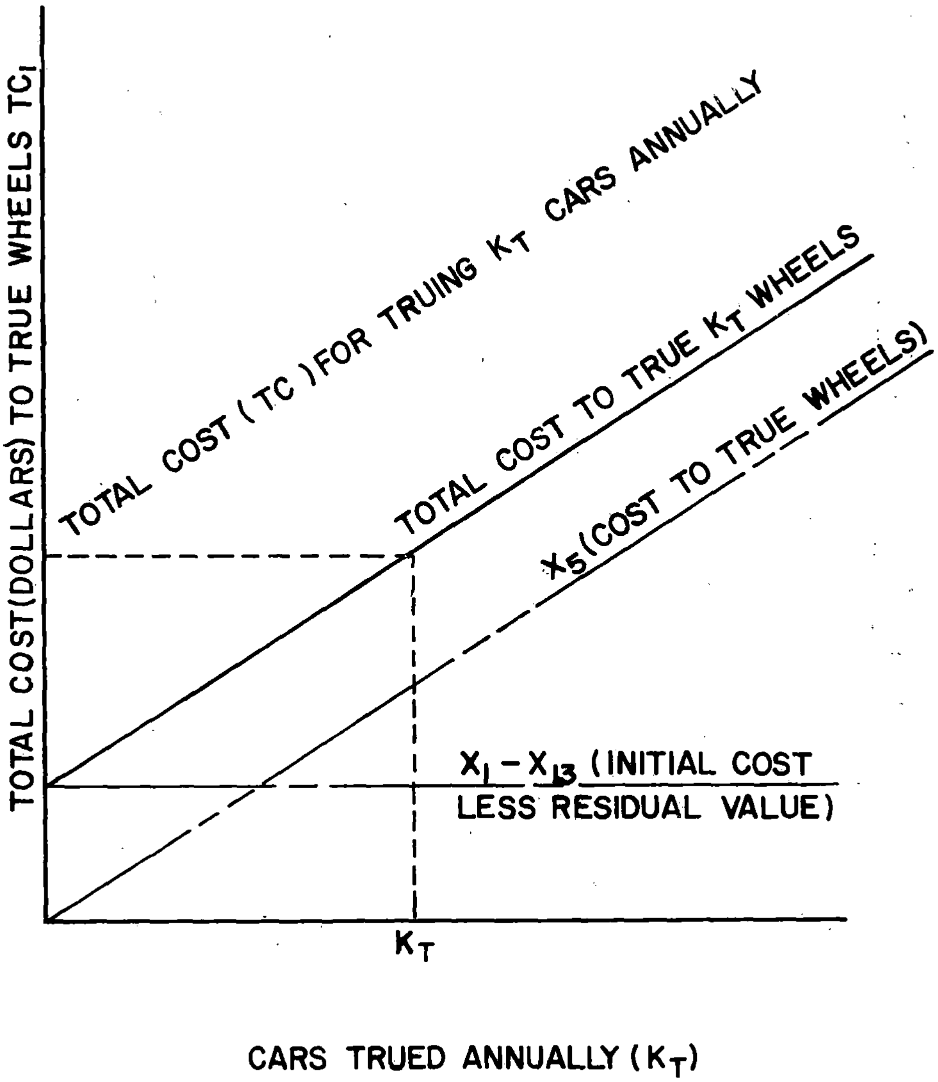
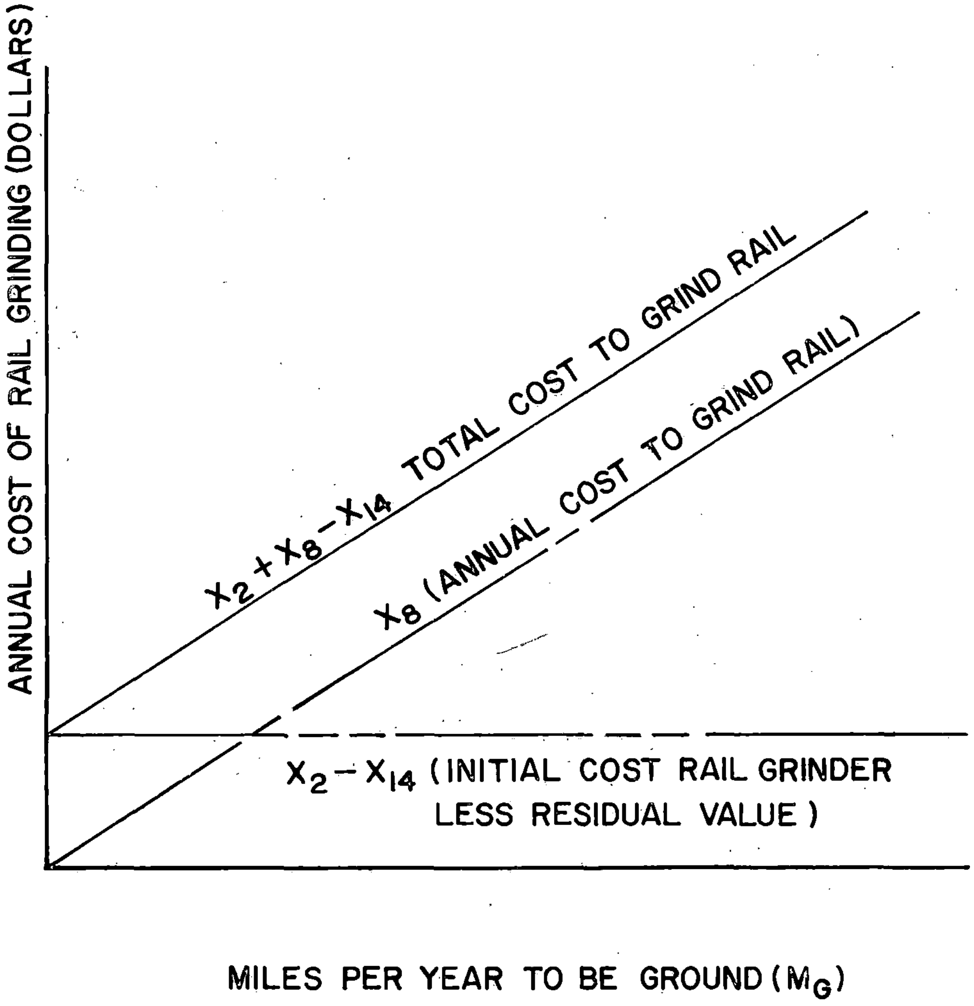


Figure 6-1 Wheel Truing Cost and Cars Trued Annually



M_G MUST BE CALCULATED FOR EACH SYSTEM

Figure 6-2 Rail Grinding Cost and Miles Ground per Year

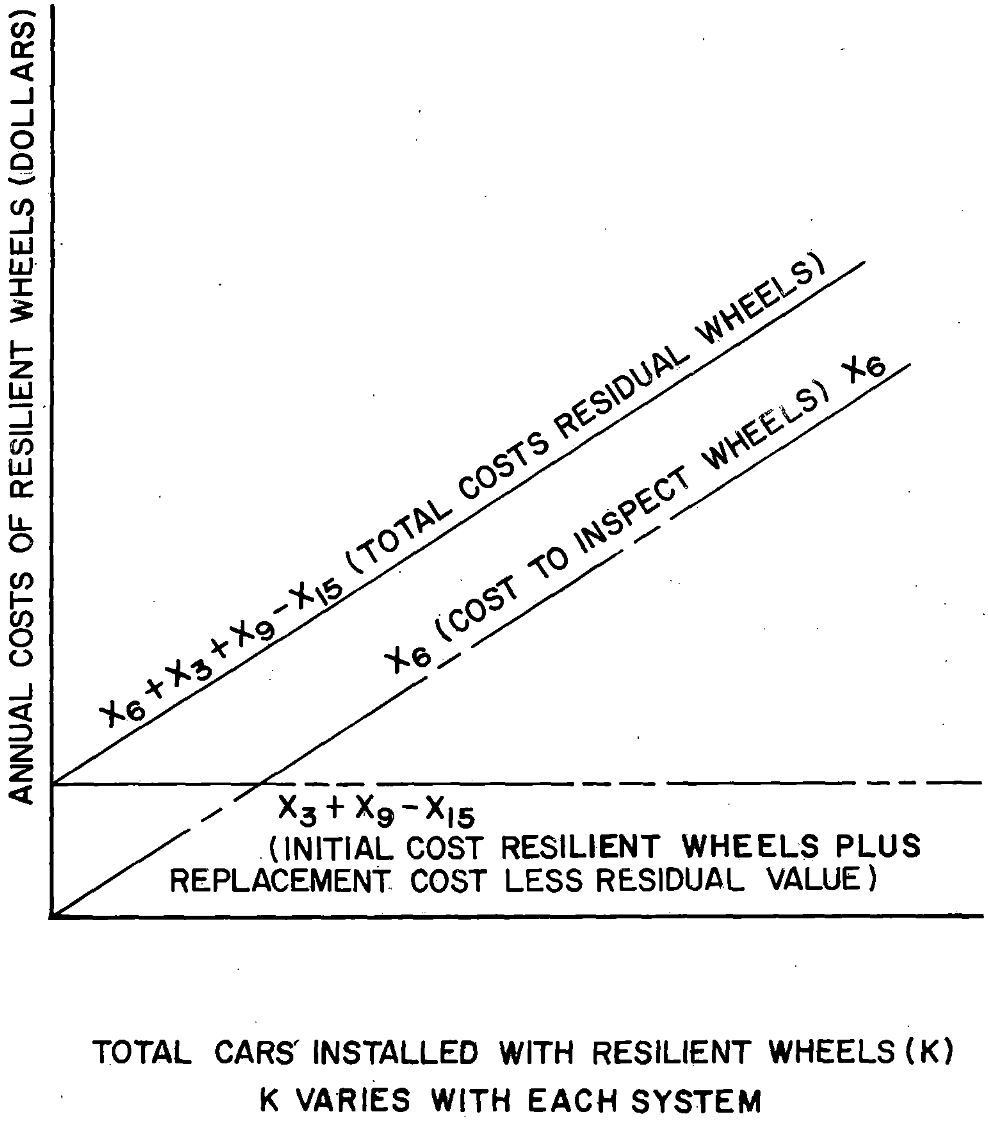


Figure 6-3 Resilient Wheel Costs and Number of Cars

APPENDIX

REPORT OF INVENTIONS

The material disclosed in this report represents a substantial improvement in the design of experiments to determine in a statistically valid manner the acoustic effectiveness and costs of noise control treatments on rail systems. A diligent review of work performed under this contract has revealed no other innovations, discoveries or improvements of inventions at this time.