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

SECOND TEST SERIES REPORT

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OCTOBER 1979

INTERIM REPORT

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16. Abstract

This report presents the results of the final four phases of the seven-phase test program whose purpose is to determine the acoustic and economic effectiveness of resilient wheels, ring-damped wheels, wheel truing, and rail grinding for reducing wheel/rail noise on urban rail transit systems. In-car and wayside noise data on both curved and tangent track are presented and discussed. In addition, the report presents information on ground-borne vibration measurements that were performed at the same time as some of the acoustical tests and a summary of the results of the propulsion equipment noise level tests. The noise from the propulsion equipment was found to limit the reduction of wheel/rail noise that could be observed in this study.

All of the testing for this project has been performed on the Market-Frankford Line of the Southeastern Pennsylvania Transportation Authority (SEPTA) rail transit system.

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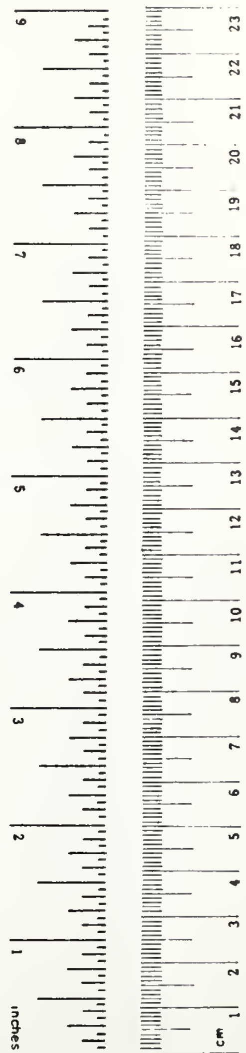
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

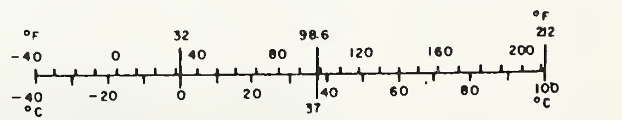
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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



PREFACE

This interim report presents the noise measurement results for the portion of the testing program performed at the SEPTA rapid transit system between October 1977 and September 1978. The overall purpose of the program is to develop information on the costs and acoustical effectiveness of four methods of controlling wheel/rail noise: resilient wheels, ring-damped wheels, wheel truing, and rail grinding. Indirectly the effect of replacing jointed rail with welded rail has also been evaluated. The ultimate goal is to provide information on the noise control methods that individual transit systems can use to evaluate the costs and benefits that would result from application of the methods. The study, sponsored by the U. S. Department of Transportation's Office of Rail and Construction Technology of the Urban Mass Transportation Administration, Office of Technology Development and Deployment, is managed by the Transportation Systems Center of the Research and Special Programs Administration under Contract (DOT-TSC-1053) as part of the Urban Rail Noise Abatement Program. This report is the fourth of the study; the first report (UMTA-MA-06-0025-76-4) covered the experimental design of the study, the second report (UMTA-MA-06-0025-77-10) presented the test and evaluation methods and procedures for determining the benefit to be gained from the noise reduction techniques examined, and the third (UMTA-MA-06-0025-78-7) presented the acoustical and cost data that had been developed as of September 1977. All reports are available through the National Technical Information Service, Springfield, Virginia 22161.

This report has been prepared by Wilson, Ihrig & Associates, Inc. (WIA) with the assistance of DeLeuw, Cather & Company (DCO). The work reported was performed jointly by personnel of WIA and DCO, principally by Hugh J. Saurenman (WIA) and Robert L. Shipley (DCO)

with significant contributions by Don Smith and Larry Ronk of DCO and George P. Wilson, Stanley M. Rosen, Armin T. Wright and Fred L. Palea of WIA. The work on this portion of the study has been technically monitored by Leonard Kurzweil of the Transportation Systems Center. The American Public Transit Association (APTA) provided significant practical contributions to this project through regular meetings of an Advisory Board for the purpose of discussing the project progress and results.

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1. INTRODUCTION

The purpose of this project, "In-Service Performance and Costs of Methods to Control Urban Rail System Noise," is to determine the acoustic and economic effectiveness of resilient wheels, damped wheels, wheel truing, and rail grinding for reducing wheel/rail noise on urban rail transit systems. Indirectly, the effects of welded rail compared to jointed has also been evaluated. At normal operating speeds, wheel/rail noise is a significant, and often dominant, component of both car interior and wayside noise. Hence, effective noise control for rail transit requires affordable and predictable techniques for redution of wheel/rail noise.

The project consists of a seven-phase series of field tests performed on the Southeastern Pennsylvania Transportation Authority System's Market Frankford Line, and in-depth interviews with management and operating personnel of the North American steel wheeled rapid transit systems regarding their experience with the above mentioned noise abatement procedures.

The U. S. Department of Transportation, Transportation Systems Center (TSC) is directing an urban rail noise abatement program for the Urban Mass Transportation Administration (UMTA) through which UMTA is sponsoring research projects to develop the technology for predictable control of acoustic noise and vibration on urban rail systems. The ultimate goal of this research is to provide sufficient information to allow a transit system with given track and car conditions and budgetary constraints to determine the mix of available noise control methods which will result in the greatest overall benefit. Included in this benefit evaluation is the reduction of noise radiated to adjacent communities and the reduction of patron noise exposure.

This project is designed to provide information on both the long-term and short-term costs and effectiveness of various wheel/rail noise abatement procedures if implemented on typical urban rail systems in the United States.

This is the fourth interim report of this study. The first two reports outlined the Experimental Design[1*] and the Test Plan[2] for the study and the third report presented the results of the first three sets of acoustical tests, the preliminary analysis of the cost data, and a summary of the survey of transit systems and manufacturers of wheel/rail noise control equipment.[3] This report presents the results of the final four sets of acoustical tests and the results of some tests completed during the first series of tests but not included in the previous report. The detailed analysis of these data along with the overall evaluation of the various noise control methods and the final evaluation of the economic data will be presented in the final report.

The following parts of Section 1 briefly describe the noise control methods, the test tracks and the test program. The summary and conclusions are presented in Section 2. Section 3 presents the results for the tests with the cars up on blocks (propolsion system noise data), Section 4 presents the wayside and car interior tests results, Section 5 discusses the vibration test results and Section 6 presents the results of the wheel decay rate tests.

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* References are listed at the end of the report.

The A-weighted sound levels for all of the tests of Phases IV, V, VI and VII are tabulated in Appendix A. Note that the data from the subway measurements of Phases I, II and III were not included in the previous interim report. Hence, the tabulation of Appendix A includes all of the subway test data. In addition, Appendix B presents average 1/3 octave band spectra for the car interior wheel squeal tests of Phases IB, IC and IIA. These figures supplement wheel squeal spectra data previously presented in Appendix D of Interim Report #3.

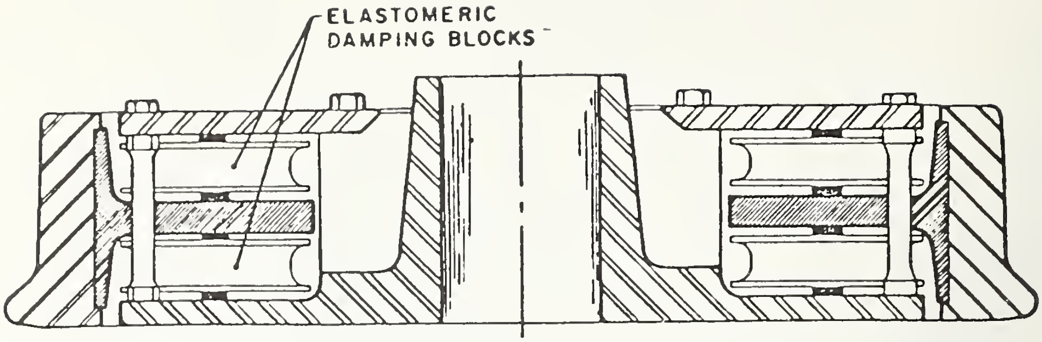
1.1 NOISE CONTROL METHODS

Four methods of reducing wheel/rail noise are included in this study: resilient wheels, damped wheels, wheel truing, and rail grinding. The data reported herewith include acoustic measurement results with standard and ring damped wheels, worn and ground rail, and worn and trued standard wheels. As discussed in the previous interim report,[3] because of problems experienced with each type of resilient wheel, the resilient wheels were removed from the study following the first three sets of tests.

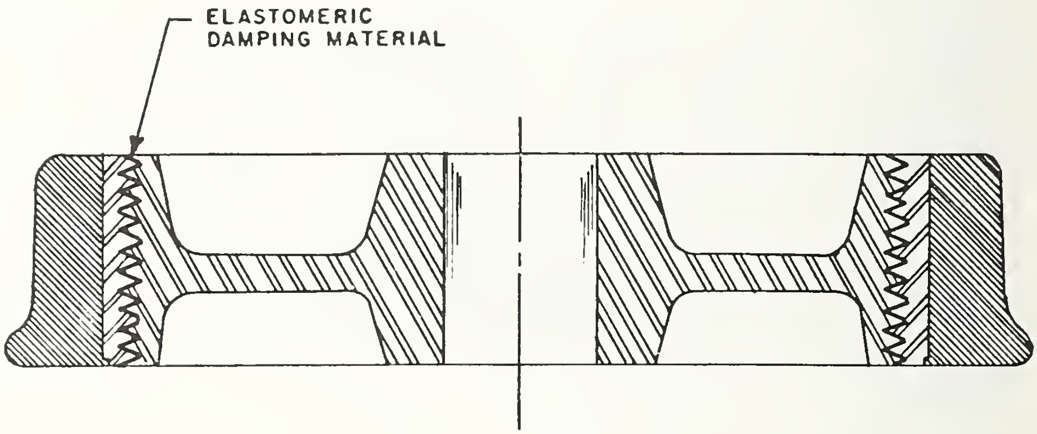
1.1.1 Resilient Wheels

The first three sets of tests included Acousta Flex, Penn Cushion (Bochum) and SAB resilient wheels. Cross-sections of these wheels are shown in Figure 1-1. The wheels are all constructed with a resilient material between the hub and the tire that acts to damp resonant vibration of the wheel and reduce transmission of vibration to the web. Problems were experienced with all three types of resilient wheels which resulted in the wheels being removed from the test program.

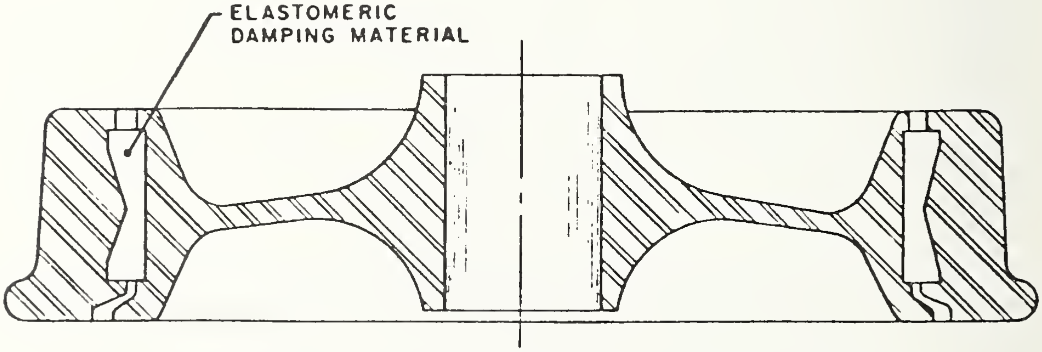
The Acousta Flex wheels were removed after a bonding failure occurred between the rim and the elastomeric material on one of the wheels, apparently due to incomplete bonding during manufacturing. One set of the Penn Bochum wheels



a. SAB RESILIENT WHEEL



b. ACOUSTA FLEX RESILIENT WHEEL



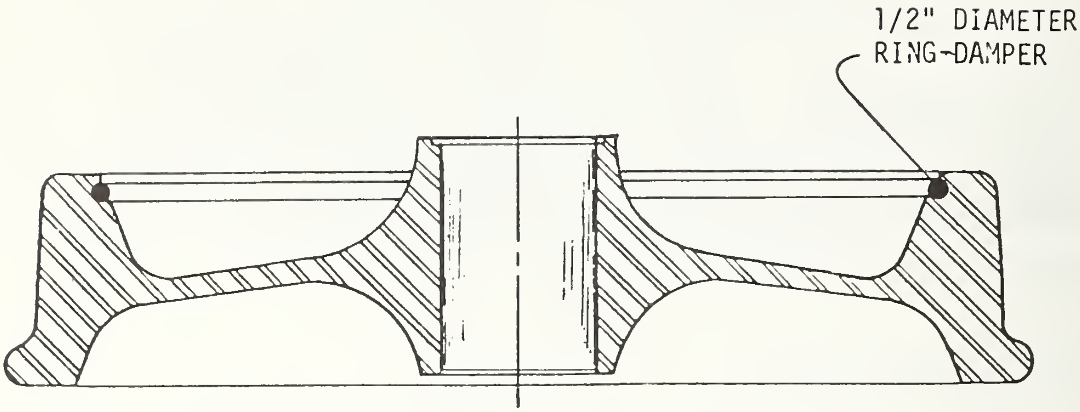
c. PENN CUSHION (BOCHUM) RESILIENT WHEEL

FIGURE 1-1. CROSS SECTION OF RESILIENT WHEELS experienced damage to the rubber blocks after a dynamic brake failure required the exclusive use of the mechanical, tread brake system. Initial imperfections of two blocks, not detected by the manufacturer's quality control system, were increased due to the combination of the resulting high wheel temperatures and the in-service compresssion stresses. The SAB wheels were removed from the program after the wheels on one axle suffered severe damage from overheating caused by application of the hand brake during revenue service.

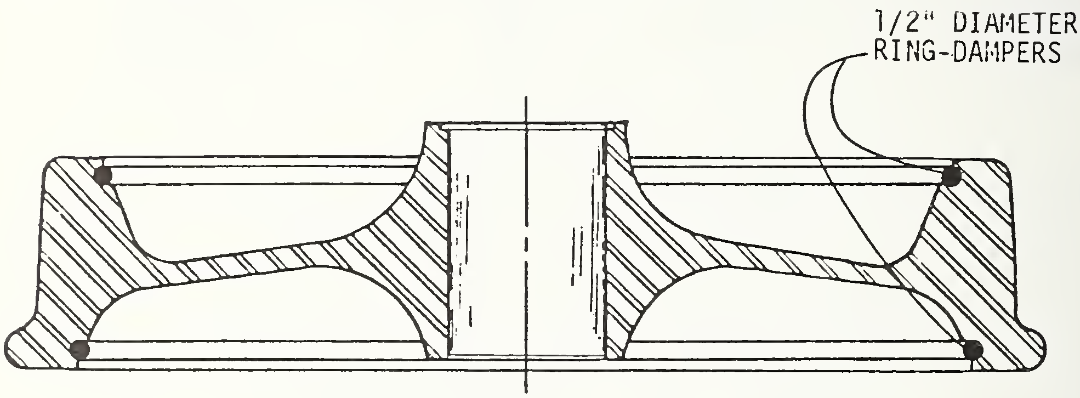
1.1.2 Damped Wheels

The original test plan included the evaluation of a 2-car set of visco-elastic damped wheels. Upon receiving the dampers, the Southeastern Pennsylvania Transportation Authority (SEPTA) did not allow them to be placed in service because of doubts concerning the ability of the dampers to stay in place under operating conditions. Subsequently, the testing of the visco-elastic damped wheels was dropped from the test program.

As a part of the second series of tests, three sets of ring-damped wheels were added to the program. As shown in Figure 1-2, ring-damped wheels consist of a mild steel ring inserted in a groove cut into the inside diameter of the wheel tread. The groove may be cut on either the field side or the flange side of the tread. Most of the tests with ring-damped wheels were performed with a 2-car set of wheels grooved on the field side. For the Phase VII tests, a series of wayside wheel squeal tests was performed with a 1-car train having wheels grooved for ring-dampers on both sides. The purpose of these tests was to compare the effectiveness of ring-dampers (on the field side, the flange side, and on both sides) in reducing wheel squeal.



a. RING-DAMPER ON FIELD SIDE



b. RING-DAMPERS ON FIELD AND FLANGE SIDES

FIGURE 1-2. CROSS SECTION OF RING-DAMPED WHEELS

By placing dampers on the flange side, the groove is placed in a location where the useful life of the tire is not affected. Cutting the groove on the field side requires removing material from the wheel tire and reduces the useful life of the wheel.

1.1.3 Wheel Truing

Wheel truing consists of grinding or machining the wheel tire running surfaces to a desired degree of smoothness, removing any non-uniformities and reducing the roughness of the running surface. The SEPTA underfloor wheel truing machine has been used to investigate the influence of wheel truing on noise radiation. The SEPTA truing machine uses milling type cutters, contoured to a standard conical wheel profile.

The new test wheels were delivered to SEPTA with the wheel surface smoothed with a lathe-type wheel truer. This allowed designing the test program to evaluate both methods of truing wheels.

1.1.4 Rail Grinding

The SEPTA rail grinding train has been used to test the noise reduction effectiveness of smoothing the rail running surface. SEPTA has a SPENO grinding train that consists of a power car and four grinding buggies having a total of 24 abrasive grinding wheels. Each grinding wheel is independently adjustable to give a smooth rail head contour.

1.2 TEST TRACKS

All of the test track sections used for this program are located on the Market Street section of the SEPTA system. Since these test tracks have been identified in some detail in two of the previous interim reports,[2,3] only a brief summary description of the test tracks is given here.

Tangent Welded Tracks on Ballasted Elevated Structure (TW)
This test section is of timber tie and ballast construction with field welded rails. It is located on elevated structure between the 60th and 63rd Street Stations. The section was divided into two 100 m segments; the Control Segment and the Test Segment. The Control Segment, serving as a reference track, remained unaltered throughout the test program except as affected by normal wear. The Test Segment rails were ground at the beginning and end of the in-service wear period for testing the effects of rail grinding.

Tangent Jointed Track On Ballasted Elevated Structure (TJ)
This section is of timber tie and ballast construction with jointed rail and is located on the elevated structure between the 56th and 60th Street Stations. The section was divided into three 100 m segments; A, B, and Control The Control Segment remained as is throughout the test program and the ramaining two segments were used to test the acoustical effects of changing joint bars to improve joint alignment and of rail grinding.

Short Radius Curve, Ballasted Track At Grade (TURN)
This test track is the inside turnaround track at the 69th Street Station, a short raduis curve on which the SEPTA

revenue trains normally create high levels of squeal noise. The section is composed of timber tie and ballasted track at-grade construction with jointed low rail, and welded high rail. The radius of curvature is approximately 43 m. The track was divided into two segments; Control and Test. The Control Segment was to remain unaltered during the test program and the Test Segment rails ground twice during the program so that before/after measurements of the effects of rail grinding could be made. However, during the first test series the Control Segment was inadvertently ground at the same time as the Test Segment removing the control aspect from the first test series at the turnaround.

Tangent Welded Track In Subway (SUB 1)

This section is composed of field welded rail fastened to timber half ties embedded in the concrete invert of the subway structure. The section, located just east of the 22nd Street Subway-Surface Station, is approximately 100 m long.

Tangent Jointed Track In Subway (SUB 2)

This section is similar to the SUB 1 track except that the rails are jointed. The section is located just east of the 19th Street Subway-Surface Station and is approximately 100 m long.

This report presents acoustical data from tests at the TW, TJ, TURN, SUB 1 and SUB 2 test tracks. The first series of acoustical tests included measurements at an elevated station with jointed track on ties and ballast, a subway station with welded track and at a switch frog on ballasted elevated structure. No tests were performed at those test tracks during the second series of tests.

1.3 TEST PROGRAM

The test program included primarily measurements of wayside noise and car interior noise for the test trains operating on the various test tracks. At the tangent tracks and the switch frog, tests were made at three different speeds; 40, 60 and 80 km/hr. At the short radius turn all measurements were at 20 km/hr and at the station test tracks measurements were made only at normal operating speeds.

To supplement the acoustical measurement data and to provide more information on the characteristics of the transit car noise generation and the results of the application of the noise reduction procedures, tests of the noise generated by the propulsion equipment, tests of the groundborne vibration produced by operation of the trains in subway, and measurements of the wheel vibration decay rate were included in the test program.

1.3.1 Wayside and Car Interior Noise Tests

The measurements of the wayside and car interior noise produced during operations on the various test tracks for the various operating conditions were divided into seven sequential phases. These tests were arranged to provide measurements of the wayside and car interior noise; before and after rail grinding; before and after wheel truing; and with resilient, damped and conventional steel wheels in both new and worn condition. Interim Report #3 presents the results from the first three phases and this report presents the results from the final four phases. The seven test phases were arranged as follows:

Phase I

The Phase I measurements of wayside and car interior noise were performed with the new standard wheel train (Cars 755/756) and the worn standard wheel train (Cars 613/623). The tests were designed to verify the noise measurement and data reduction procedure, establish variation between Test and Control track segments, document noise levels produced by new and worn standard wheels on worn and ground rail, and investigate differences between new lathe turned wheels and standard wheels trued with a milling cutter type of truing machine.

Phase II

The Phase II measurements of wayside and car interior were performed after the three sets of resilient wheels had been installed. The tests included the resilient wheels and both the worn and trued standard steel wheels on all types of track before and after rail grinding.

Phase III

Phase III was an abbreviated set of noise measurements performed approximately six months after Phase II to determine the effects of in-service wear on the wheels and rails. Originally Phase III was to include only car interior noise measurements, however, because the problems experienced with the resilient wheels forced removing all of the resilient wheels from the study after Phase III, the Phase III testing was expanded to include wayside noise measurements at the TW and TURN test tracks.

Phase IV

The original purpose of Phase IV was to evaluate all combinations of worn wheels and worn rails after a one year in-service wear period by measuring both wayside and car interior noise. However, of the five original test trains, only the worn standard wheels and the new standard wheels were still in operation. It is at this point that the ring-damped wheels [new standard steel wheels with ring-dampers installed] were added to the study. Hence, the Phase IV tests included the worn standard wheels, the new standard wheels which had been used in service, the ring-damped wheels with dampers installed, and the ring-damped wheels with the dampers removed. The ring-damped wheels used at this point were new with no in-service wear. The tests were performed on the TW, TJ, TURN, SUB 1 and SUB 2 test tracks.

Phase V

After Phase IV all of the Test Segments [but not Control Segments] of the test track rails were ground and the acoustical measurements of Phase IV repeated.

Phase VI

After Phase V all of the test wheels including the ring-damped wheels were trued and car interior and wayside noise tests were performed on the TW and TURN test tracks which had the Test Segments in newly ground condition and the Control Segments in worn condition. At this time the TW Control Segment had approximately two years of wear since grinding and the TURN Control Segment one year of wear since grinding.

Phase VII

Because of the success of the ring-damped wheels in reducing squeal noise, as observed during the Phase IV, V and VI tests, the testing was expanded to include a final test series on the TURN test track with a second set of ring-damped wheels. The second set of ring-damped wheels had grooves cut on the flange side and the field side of the wheel. In this final test series the worn ring-damped wheels (with grooves on the field side) were tested with the rings in and the rings out and the new ring damped wheels (with grooves on both sides) were tested with rings out, rings in the field side, rings in the flange side and rings in both sides.

1.3.2 Propulsion Equipment Noise Tests

On most transit cars at normal operating speed, noise generated by the propulsion equipment, primarily the traction motors and gear boxes, is of the same order of magnitude as the wheel/rail noise. There are some instances where other noise sources may be important components, but wheel/rail noise and propulsion equipment noise generally dominate.

The purpose of all the noise control methods tested in this study is to reduce the wheel/rail noise. Obviously, if the noise from the propulsion equipment dominates the overall noise levels, it is impossible to determine the effectiveness of the noise control methods from direct measurements of car interior and wayside noise.

To help evaluate the relative levels of wheel/rail noise and propulsion equipment noise, several tests were performed with cars supported on blocks allowing the wheels to spin freely. Because the major portion of car equipment noise is generated by the drive motors, measurement of the noise with the wheels spinning freely provides a valid measure of the car equipment noise. During normal operation with the gears and motors loaded there may be some additional gearbox noise; however, in most cases it has been found that gearbox noise is less than or, at most, comparable with the noise from the propulsion motors. The motors generate the same noise whether loaded or unloaded because the predominant sources of noise are the cooling fan and normal motor windage noise. Both of these noise sources are independent of load on the motor.

The noise with the cars on blocks was measured on three separate occasions. All of the data obtained are presented in summary form in Section 3.

1.3.3 Ground-Borne Vibration Tests

At many transit systems the structure-borne vibration created at the wheel/rail interface results in noise and vibration intrusion inside adjacent structures. The vibration produced at the wheel/rail interface by the wheels rolling on the rails is transmitted from the transit structure through the ground to nearby structures. The vibration of the building structure is sometimes perceptible as mechanical motion and more often appears as a low frequency rumbling noise radiated from the room surfaces inside buildings, i.e., as structure-borne noise.

The acoustical tests of the methods to reduce wheel/rail noise presented a unique opportunity to evaluate the effectiveness of the same methods at reducing the vibration levels. Vibration measurements were performed simultaneousy with several of the acoustical tests of Phases I and II. The vibration data were collected by personnel of the Port Authority of New York and New Jersey at measurement locations at the Test Segment of the TW test track and the tangent welded subway test track [SUB 1].

The results of the vibration measurements are presented in Section 5. The data collected include tests with new resilient wheels, worn standard wheels, and trued standard wheels, all on tangent welded track with the rails worn and recently ground for subway test track [SUB 1], and in recently ground condition on the TW test track.

1.3.4 Wheel Vibration Decay Rate

One of the primary design goals for the resilient and damped wheels is the achievement of high damping factors to reduce vibration amplitudes and thereby reduce noise radiation. The higher the damping factor of the wheels the less likely squeal will occur on short radius curves.

A short series of tests was performed to measure the loss factors as a function of frequency using the resilient, ring-damped, and standard wheels. The method used was to measure the vibration decay after impacting the wheels. The results of these tests are presented in Section 5.

2. SUMMARY AND CONCLUSIONS

At the time of preparation of this report, the in-service performance and cost study of methods for reducing urban rail system noise has progressed to the completion of the field measurement portion of the program. Interim Report #3 was prepared after the first three phases of acoustic measurements were completed and after the cost data from transit properties and manufacturers had been assembled. This Interim Report presents the results from the second series of field tests, referred to as Test Series 2, which includes the final three phases of the originally planned acoustic testing and an added seventh phase (additional ring-damped wheel tests) which was instituted because of the excellent performance obtained from the ring-damped wheels in the early Series 2 tests. The report also includes data and results from wheel damping factor tests, structure-borne and ground-borne vibration tests and the results of a set of propulsion equipment noise tests supplementary to those tests reported in Interim Report #3.

2.1 SERIES 2 ACOUSTIC TEST RESULTS

The basic data obtained from the acoustic tests of Series 2 were the change in noise levels at the various test tracks resulting from one to two years wear of wheels and rails and from the effects of rail grinding and wheel truing performed to attempt to return the wheels and rails to the condition present at the beginning of the test program. Further, Test Series 2 included the introduction of ring-damped wheels to the test program. Thus, Test Series 2 included measurements with: new (lathe-turned), trued and worn standard steel wheels; ground and worn rail; and ring-damped wheels. Because of the problems experienced with the resilient wheels in the early part of the program, they could not be included in Test Series 2.

The test tracks included tangent welded ballast and tie track, tangent jointed ballast and tie track, short radius curve on ballast and tie, and subway tracks with both tangent jointed and tangent welded rail. All welded rail on SEPTA is field welded, there is no shop welded rail. The results for these combinations of wheel and rail conditions are presented and analyzed in the results section of this Interim Report.

The results of the noise level measurements lead to the following general observations and conclusions:

Propulsion Equipment Noise

The tests of propulsion equipment noise indicate good correlation between trains. The 600 series and 700 series cars have approximately the same levels of noise in the car interior (after the pure tones are removed). At the wayside the propulsion system noise from the 700 series cars is 3 to 4 dBA less than that from the 600 series cars.

The propulsion equipment noise limits the reduction of wheel/ rail noise that can be observed in this study, however, all of the passby noise data from the Test Series 2 appears to be at least 5 to 5 dBA above the propulsion equipment noise. This indicates that propulsion equipment noise, in many cases, was a major component of the overall noise level and some of the relatively small measured reductions in overall noise level were influenced by the propulsion equipment. However, in some cases where small changes in total noise were observed, this was because of a correspondingly small change in wheel/rail noise.

Rail Grinding

a. On tangent track there was no identifiable change in noise level due to rail grinding in Test Series 2. The results of Test Series 1 showed that grinding the Test Segments reduced both the wayside and car interior noise level, whereas Test Series 2 results showed no significant change. Apparently, the rail and joint condition did not deteriorate sufficiently between Test Series 1 and Test Series 2 to be significantly improved by the rail grinding included in Test Series 2.

b. At the curve track rail grinding was found to reduce squeal by 3 to 4 dBA in Test Series 2. In Test Series 1 the noise levels were found to increase after rail grinding. The rail grinding tests on the curve track were more controlled in Test Series 2. The overall observation is that the effects of rail grinding on squeal noise are inconsistent. It can be concluded that rail grinding cannot be used to consistently and predictably reduce squeal noise on curves as other factors such as moisture and vehicle condition appear to have greater effects on the squeal noise.

Wheel Truing

a. For Test Series 2 on tangent track the noise levels generally increased after wheel truing. The wheels were tested just after truing, and the noise level increase was apparently due to the cutter marks from the truing machine on the wheel tread surface. This phenomenon was not observed in Test Series 1 when the wheels had several days of revenue service wear after being trued before they were tested.

   The new wheels, characteristic of wheels trued with a lathe-type truer, were consistently 2 to 4 dBA quieter than wheels with 28 months of wear.

b. The wheel squeal levels were consistently lower with smoothed wheels than with the worn wheels. The wayside levels of wheel squeal with new and trued wheels averaged 6 dBA lower than worn wheels on worn rail and approximately 4 dBA lower on ground rail.

Ring-Damped Wheels

a. The Test Series 2 data do not provide any evidence of noise reduction on tangent track from the use of ring-dampers.

b. Ring-dampers not frozen in the grooves provide significant internal damping above 1400 Hz and are very effective at controlling wheel squeal.

c. Ring-dampers frozen in the grooves due to corrosion or other mechanisms are ineffective as dampers.

d. The noise data from these tests do not indicate any advantage to be gained from placing the grooves for the ring-dampers on the field side or the flange side.

2.2 SUPPLEMENTARY TEST RESULTS

The in-service performance and cost study program includes some tests of the effects of damped and resilient wheels and of the rail grinding and wheel truing, other than the acoustic performance tests. Specifically, tests of wheel damping factors have been included to provide a simple test giving data which correlates with wheel squeal phenomena. Secondly, a series of structure-borne and ground-borne vibration tests was included to provide information on the effects of the rail grinding, wheel truing and resilient wheels on ground-borne vibration levels. The general observations and conclusions from these tests are:

Wheel Damping Factor Tests

a. Loss factors can be accurately measured using simple vibration decay techniques.

b. Wheel squeal is highly correlated to loss factor, the probability and magnitudes of wheel squeal decreasing as loss factor increases.

c. The resilient wheels have much higher effective internal damping than the standard wheels over the squeal frequency range. The Penn Bochum wheels had the highest damping and the SAB wheels the lowest damping of the resilient wheels.

d. The ring-dampers do not provide damping below about 1400 Hz. Above 2000 Hz the ring-dampers result in effective damping of wheel vibration and, in fact, produce about the same or higher damping than the SAB wheel configuration.

Ground Vibration

a. The ground vibration tests showed the resilient wheels to produce 5 to 10 dB lower ground-borne vibration levels than the trued standard wheels for the frequency range above 16 Hz. Some of the vibration data with the trued standard wheels had evidence of wheel flat impacts which could be partially responsible for the difference. Wheel flats were not visually identifiable on the wheels.

b. Over most of the frequency range the resilient wheels resulted in essentially identical ground vibration characteristics except for the SAB wheels which showed consistently lower levels for the 20 to 80 Hz range.

c. The worn standard wheels created 3 to 10 dB higher vibration levels than the trued standard wheels over most of the frequency range. This result was partially due to wheel flat impacts. The wheel flat impacts were clearly identifiable on many of the vibration data samples with the worn standard wheels.

d. The before/after rail grinding results in the subway showed 3 to 8 dB reduction of invert and adjacent building floor vertical vibration and no change in the rail vertical vibration.

3. PROPULSION EQUIPMENT NOISE TEST RESULTS

The overall purpose of this program is to evaluate the reduction of wheel/rail noise that can be achieved in service on an operating transit system. For most transit cars the noise from the propulsion equipment is on the same order of magnitude as the roar noise generated by the wheels rolling on the rail - the wheel/rail noise. Since on the SEPTA cars the propulsion motors and the gearboxes cannot be disengaged from the axles, the reduction of wheel/rail noise that can be observed in this study is limited by the noise from the propulsion equipment.

The noise from the propulsion equipment was evaluated by supporting the test cars on blocks such that the wheels could spin freely. With the wheels spinning freely and all of the auxiliary equipment operating it is possible to duplicate the conditions of the moving train tests without wheel/rail noise. The only differences that may have some influence on the noise levels are the train being approximately 10 cm higher above the trackbed than normal and the fact that the gears operate at a no-load condition.

The change in the train elevation may slightly increase the wayside levels by reducing the amount of noise "trapped" under the car and absorbed by the ballast. Since the elevation change is relatively small the influence on the noise levels should be small.

The fact that the propulsion equipment is operating under the no-load condition also has only a minor influence on the noise level. During normal operation with the gears and motors loaded there may be some additional gearbox noise;

however, the propulsion system noise level performance tests for the BART, WMATA Metro and new CTA cars show that in most cases the gearbox noise is less than or at most comparable with the noise from the propulsion motors. The motors generate the same noise whether loaded or unloaded because the predominant sources of noise are the cooling fan and normal windage noise, noise sources which are independent of load. The net result is that propulsion equipment noise is only slightly, if at all, influenced by load.

Tests of propulsion equipment noise were performed on three separate occasions. The first test was performed in April 1976 with Car 613, one of the cars from the worn standard wheel train. The second test was performed in July 1976 with the new standard wheel train, Cars 755 and 756, a married pair.* The third test was performed in December 1977 with the worn standard wheel train, the new standard wheel train and the ring-damped wheel train; Cars 613/623, 755/756, and 607/644, respectively.

Table 3-1 indicates the results of the measurements 7.5 m from the track centerline. These are the average of measurements at several positions (a minimum of three) along the train. The car interior measurements presented in Table 3-2 are the average of measurements at the car center and over a truck at one end of the car.

At the same time as the acoustical measurements, measurements of the wheel RPM were also performed to allow estimating

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*A married pair car set is one that is permanently coupled. Typically the 2-car set will share auxiliary equipment. Cars 755/756 were the only married pair in the test program; all the rest of the test cars could operate as single cars.

TABLE 3-1. WAYSIDE NOISE MEASUREMENTS OF PROPULSION EQUIPMENT NOISE - AVERAGE, 7.5 METERS FROM TRACK CENTERLINE

Car	Date	Equivalent Average Speed - km/hr	Sound Level - dBA	
			With Tone[1]	Without Tone[2]
613	4/76	50	77.6	74.4
		100	92.7	87.7
613/623	12/77	43	76.9	75.0
		107	94.8	91.4
623	12/77	55	78	77.4
		125	98	91.1
755	7/76	64	77.5	75.0
		105	85.5	83.8
756	7/76	54	78.9	76.2
		107	85.5	83.3
755	12/77	40	71.8	68.6
		87	86.5	79.0
755/756	12/77	55	77.8	72.4
607/644	12/77	48	75.6	75.1
		61	80.2	77.7
		107	96.0	90.8

[1] Sound level as measured.

[2] With effects of tonal noise from motor cooling fans removed.

TABLE 3-2. CAR INTERIOR NOISE MEASUREMENTS OF PROPULSION EQUIPMENT NOISE - AVERAGE OF MEASUREMENTS AT CAR CENTER AND OVER TRUCK

Car	Date	Equivalent Average Speed - km/hr	Sound Level - dBA	
			With Fan[1]	Without Fan[2]
613	4/76	50	69.3	67.7
613	4/76	100	82.2	76.9
613	12/77	100	85.9	80.4
623	12/77	55	70.0	68.6
623	12/77	120	86.8	81.8
756	7/76	54	70.6	70.6
756	12/77	70	72.4	69.8
756	12/77	120	90.1	83.0
755	12/77	100	81.5	79.8
607	12/77	76	79.2	74.8
644	12/77	76	78.2	75.4
644	12/77	90	82.4	78.2

[1] Sound level as measured.

[2] Sound level with effects of tonal noise from motor cooling fans removed.

the equivalent train speed. In the first two tests the RPM was measured with a photo tachometer and the results recorded by hand. In the third test the RPM was measured using a generator that produces a voltage proportional to RPM. The generator has a friction drive activated by pressing against a spinning wheel. The RPM was read directly in the field from a calibrated meter. In addition the signal from the generator was recorded on the FM channel of the Nagra IV SJ tape recorder for subsequent analysis.

As discussed in Interim Report #3, analysis of the data from the first two cars-on-blocks measurements revealed a pure tone component of the propulsion equipment noise at the blade passage frequency of the traction motor cooling fan. The frequency of this component is equal to 13.1 times the train speed or 1.75 times the wheel RPM. At high train speeds it was found that this tonal noise dominated the overall A-weighted passby noise level. Hence the data analysis system was modified to include a notch filter that was tuned to the blade passage frequency of the fan for the measured speed of each passby. Figure 3-1 shows an example of propulsion equipment noise analyzed with and without the notch filter. The notch filter was tuned to 1400 Hz for this particular data set, and as is evident, the tonal noise is effectively removed.

One significant obstacle in obtaining valid data on propulsion equipment noise was the variation of RPM. Each axle is powered by a separate traction motor. In the first two test series the RPM was found to have some axle-to-axle variation - generally the variation on one car was less than 30%. However in the third series of tests wide fluctuations in axle speed were observed - in one case there

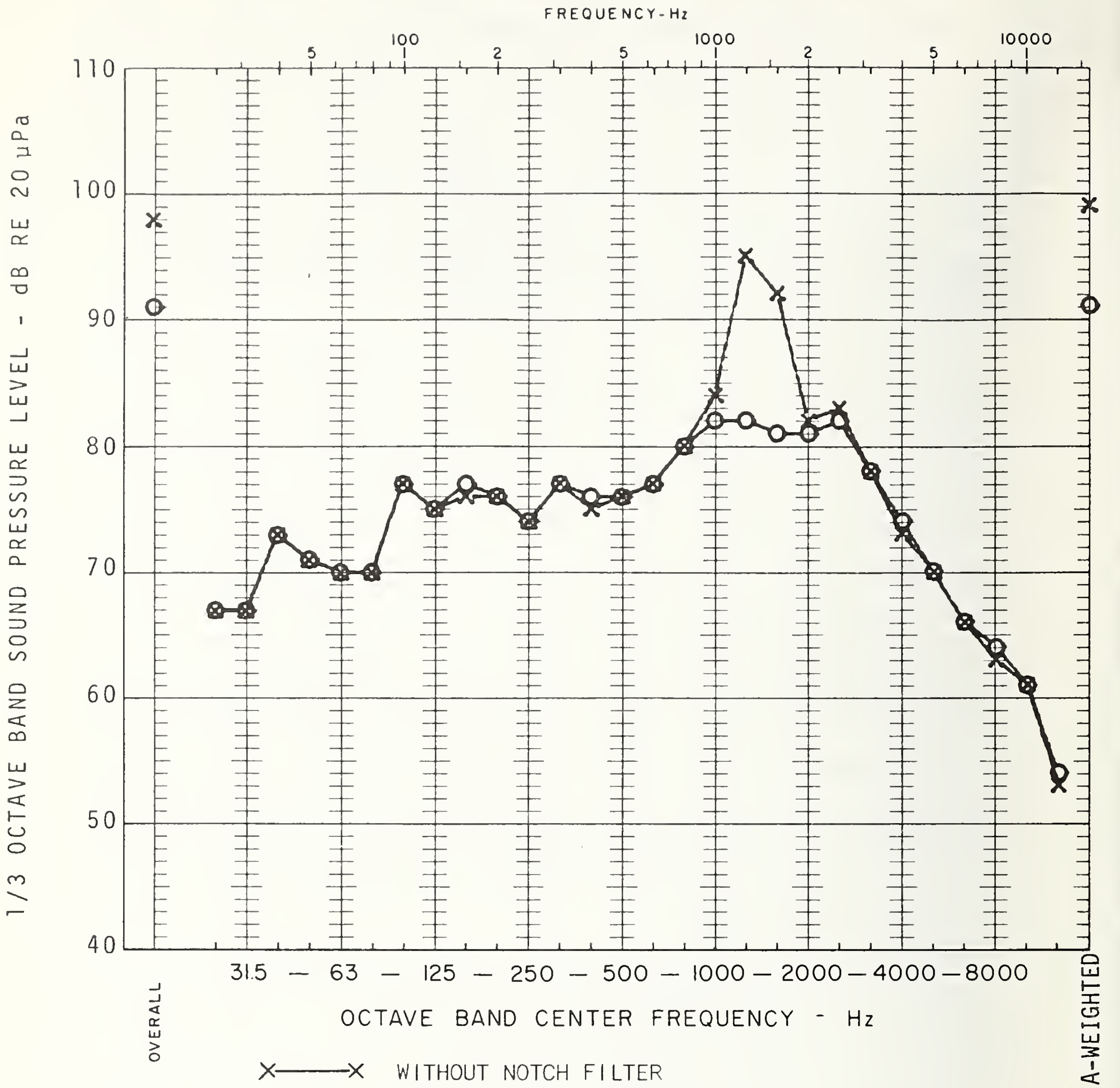


FIGURE 3-1. PROPULSION EQUIPMENT NOISE ANALYZED WITH AND WITHOUT NOTCH FILTER - 7.5 M FROM TRACK CENTERLINE - CARS 607/644

EQUIVALENT TRAIN SPEED = 110 KM/HR

was a 10 to 1 ratio between the axle speeds on one truck. Apparently a balancing mechanism was inoperative on the test cars during the third test series. For the cases where there were wide variations in axle RPM several different techniques for determining an appropriate average speed or adjusting the data to account for the variations in axle rotation speed were investigated. The first technique was to assume that each of the axles are identical omnidirectional point sources radiating noise proportional to axle speed to the fourth power. The noise level at each wayside measurement position could then be normalized to one speed. However, this technique resulted in very inconsistent results. In one case the normalized level was higher than actually observed at the wayside. The inconsistencies were only marginally improved with adjustments to the speed proportionality factor. The inconsistencies tend to indicate that the motors are not omnidirectional noise radiators and that there are significant variations in the noise radiation characteristics of the various motors caused by the location in the truck and location relative to the wheels, truck frame and car body.

The technique used to determine the average speed for the third series of tests was to calculate an "equivalent" speed using the formula

$$\bar{V} = \left(\frac{1}{n} \sum_{i=1}^{n} V_i^5\right)^{1/5}$$

where n = number of axles

V_i = speed of ith axle

$\bar{V}$ = equivalent speed.

In most cases this provided consistent results, and the tonal peak caused by the traction motor fan noise was in the appropriate 1/3 octave band. However, there were several cases where the peak due to the fans was at considerably higher frequencies than predicted by the equivalent speed. In these cases the "equivalent" speed was adjusted to be consistent with the observed peak frequencies, that is

$$\bar{V} = f_p/13.1$$

where f_p = peak frequency.

As shown in Figures 3-2 and 3-3 the resulting data points show good correlation.

Tables 3-1 and 3-2 present the A-weighted levels as measured and the A-weighted levels with the effects of the fan tonal noises removed. To estimate the A-weighted levels without the tonal noises, the 1/3 octave bank spectra were adjusted to remove the tonal noise peaks. Then the A-weighted levels were calculated by summing the 1/3 octave bank levels. Because of the variations in axle speed it was not possible to use the tunable notch filter to remove the pure tone noises directly for the third series of tests.

Figure 3-2 presents the wayside noise levels as a function of speed and distinctly shows the difference in noise generation characteristics for the two types of cars. The married pair cars (755/756) generated wayside levels approximately 3 to 5 dBA lower than for the single cars. Note that the data indicate that for the married pair cars, the wayside noise is proportional to $V^{3.3}$ but for the single cars is proportional to $V^{4.1}$. The data also indicate that operating two cars typically increases the level

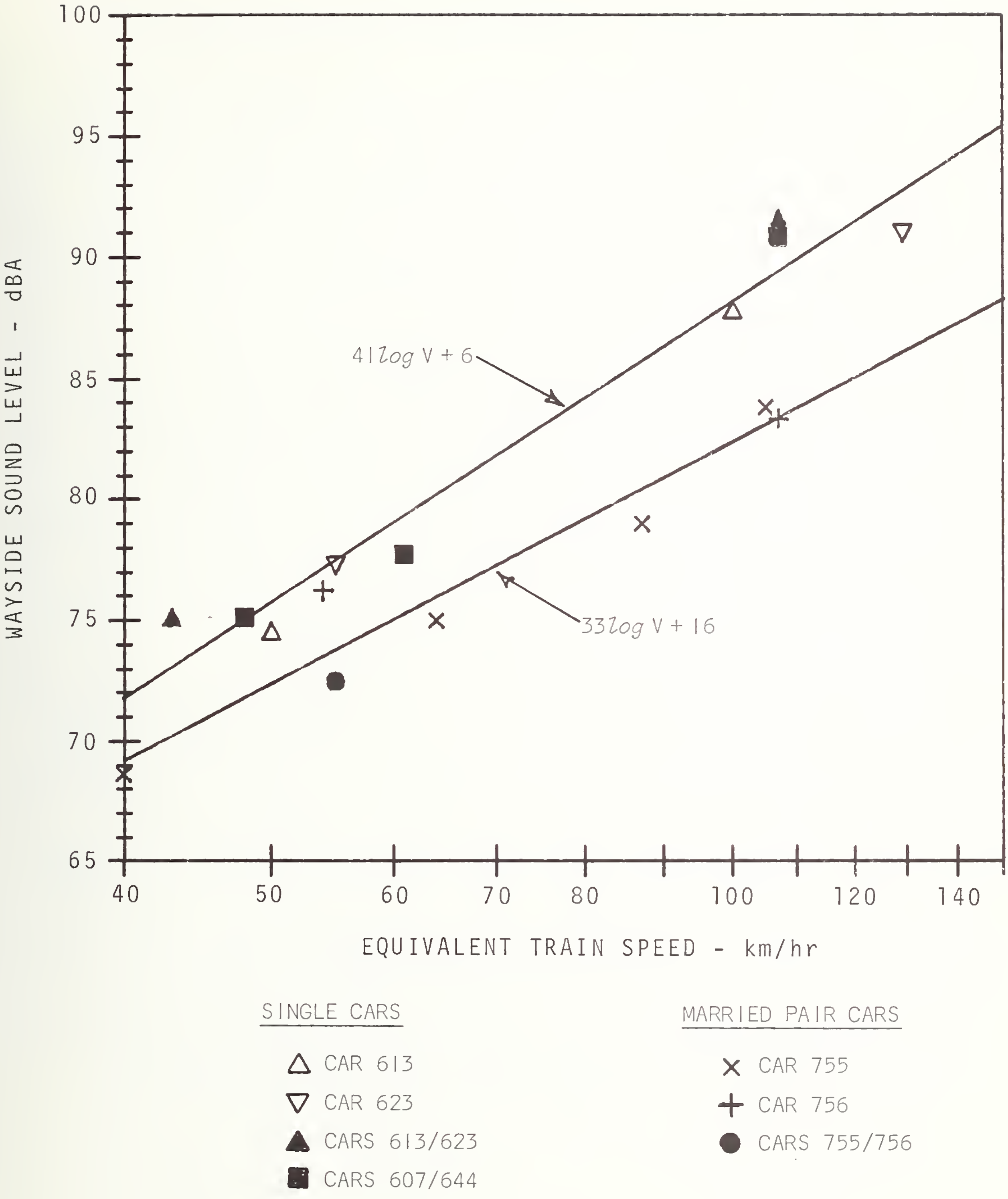


FIGURE 3-2. WAYSIDE NOISE LEVEL FOR PROPULSION EQUIPMENT AS A FUNCTION OF SPEED - 7.5 m FROM TRACK CENTERLINE [PURE TONE COMPONENTS REMOVED]

by a maximum of 1 to 2 dBA compared to a single car; however, in some cases no increase was observed. The noise data as a function of speed for the car interior measurements, shown in Figure 3-3, do not indicate any significant differences between the married pair cars and the single cars. For the interior noise, the overall A-weighted level is proportional to $V^{3.8}$.

The wayside and car interior noise data from propulsion equipment are of similar levels and characteristics found for other rapid transit cars.

Figures 3-4, 3-5, and 3-6 provide a comparison of the spectra for specific examples of overall train noise and propulsion equipment noise. Since these are specific spectra, caution must be used in drawing generalized conclusions. The spectra in Figure 3-4 show that, for the single car type trains, below approximately 500 Hz the wayside noise is dominated by wheel/rail noise and the propulsion equipment noise are of the same order of magnitude on the tangent welded track.

Figure 3-5 compares the overall wayside noise and propulsion equipment noise for Cars 755/756, the married pair set of cars. The spectra for both the wayside noise and the propulsion equipment noise have shapes very similar to those for the single cars - Figure 3-4. The primary difference is that above 125 Hz the propulsion equipment noise spectrum for the married pair cars is 2 to 5 dB less than for the single cars. The spectrum for propulsion equipment noise shown in Figure 3-5 is the average of the data for Car 755 with an equivalent speed of 64 km/hr (taken in July 1976) and that for Cars 755/756 with an equivalent speed of 58 km/hr (taken in December 1977).

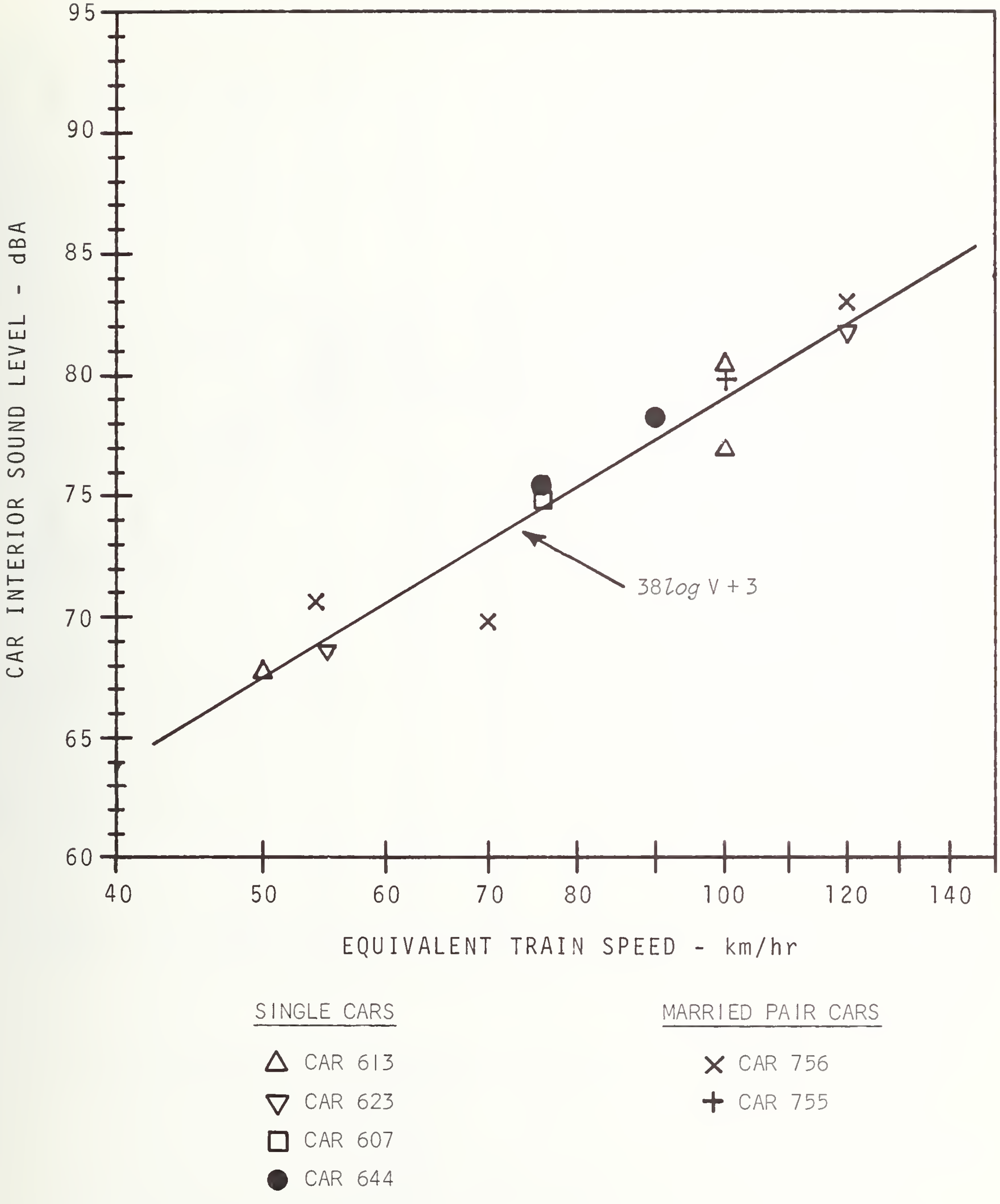


FIGURE 3-3. LEVELS OF PROPULSION EQUIPMENT NOISE AS A FUNCTION OF SPEED - CAR INTERIOR [PURE TONE COMPONENTS REMOVED]

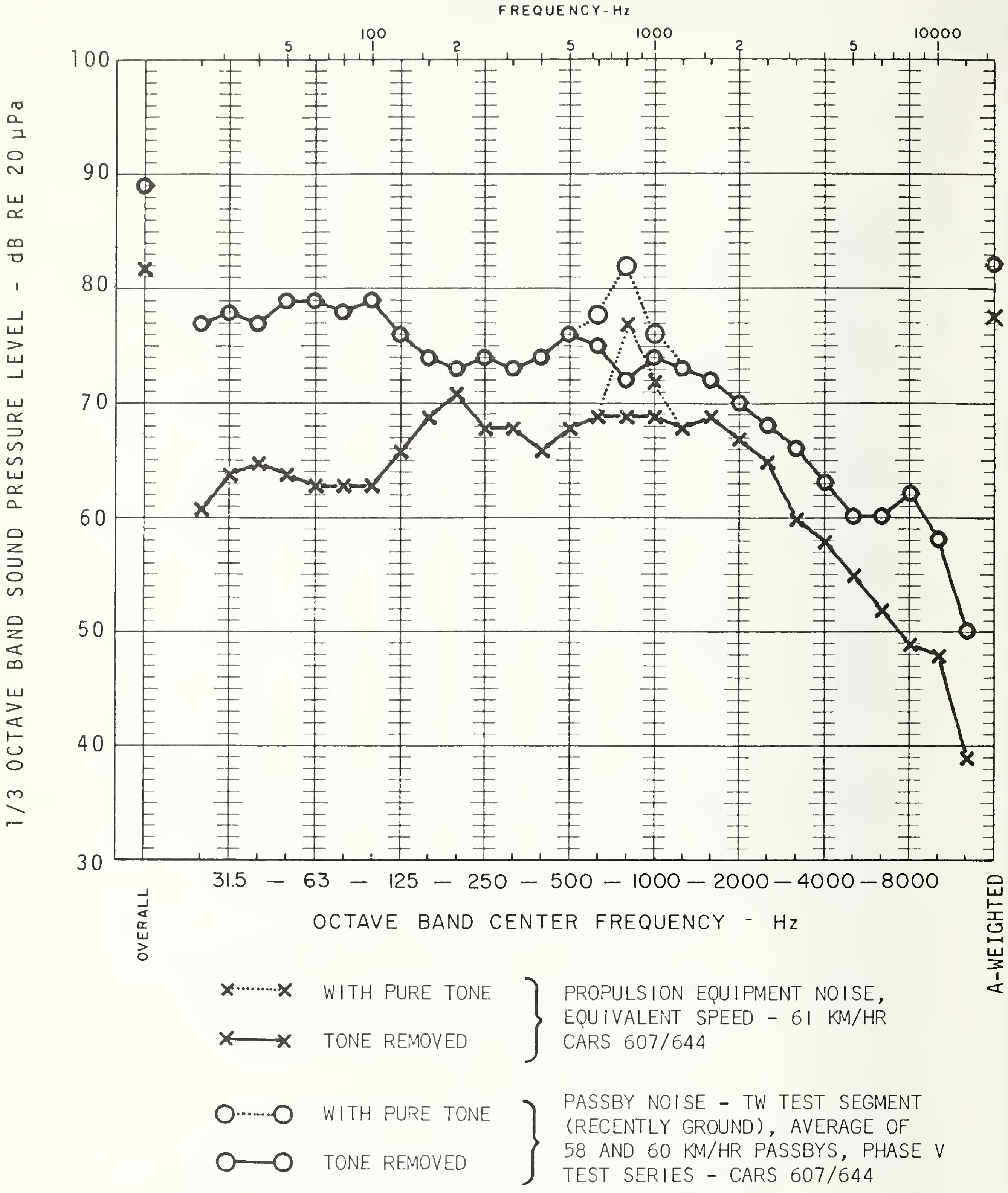


FIGURE 3-4. COMPARISON OF SPECTRA OF PROPULSION EQUIPMENT NOISE AND PASSBY NOISE - 7.5 m FROM TRACK CENTERLINE

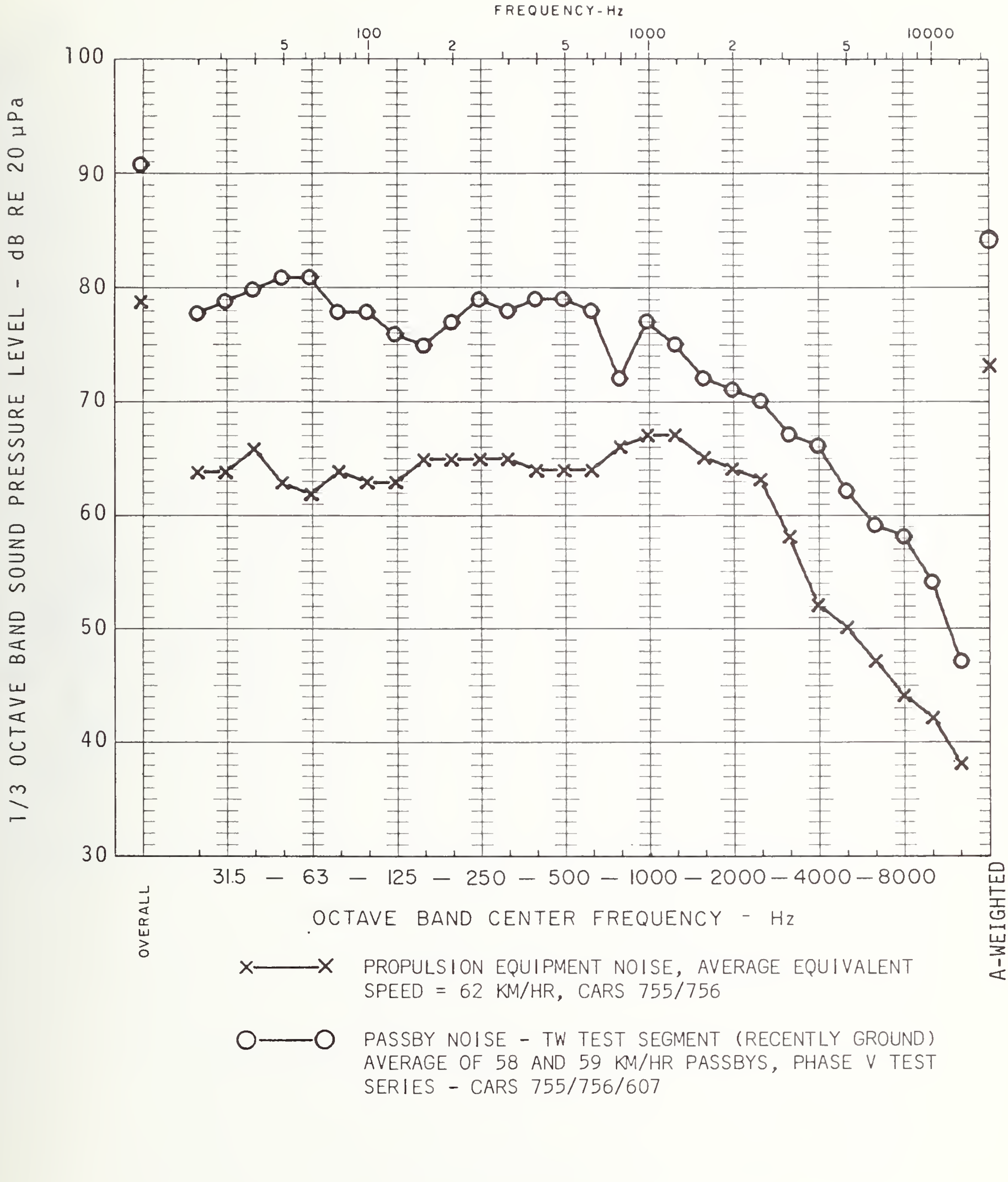


FIGURE 3-5. COMPARISON OF SPECTRA OF PROPULSION EQUIPMENT AND PASSBY NOISE - 7.5 M FROM TRACK CENTERLINE

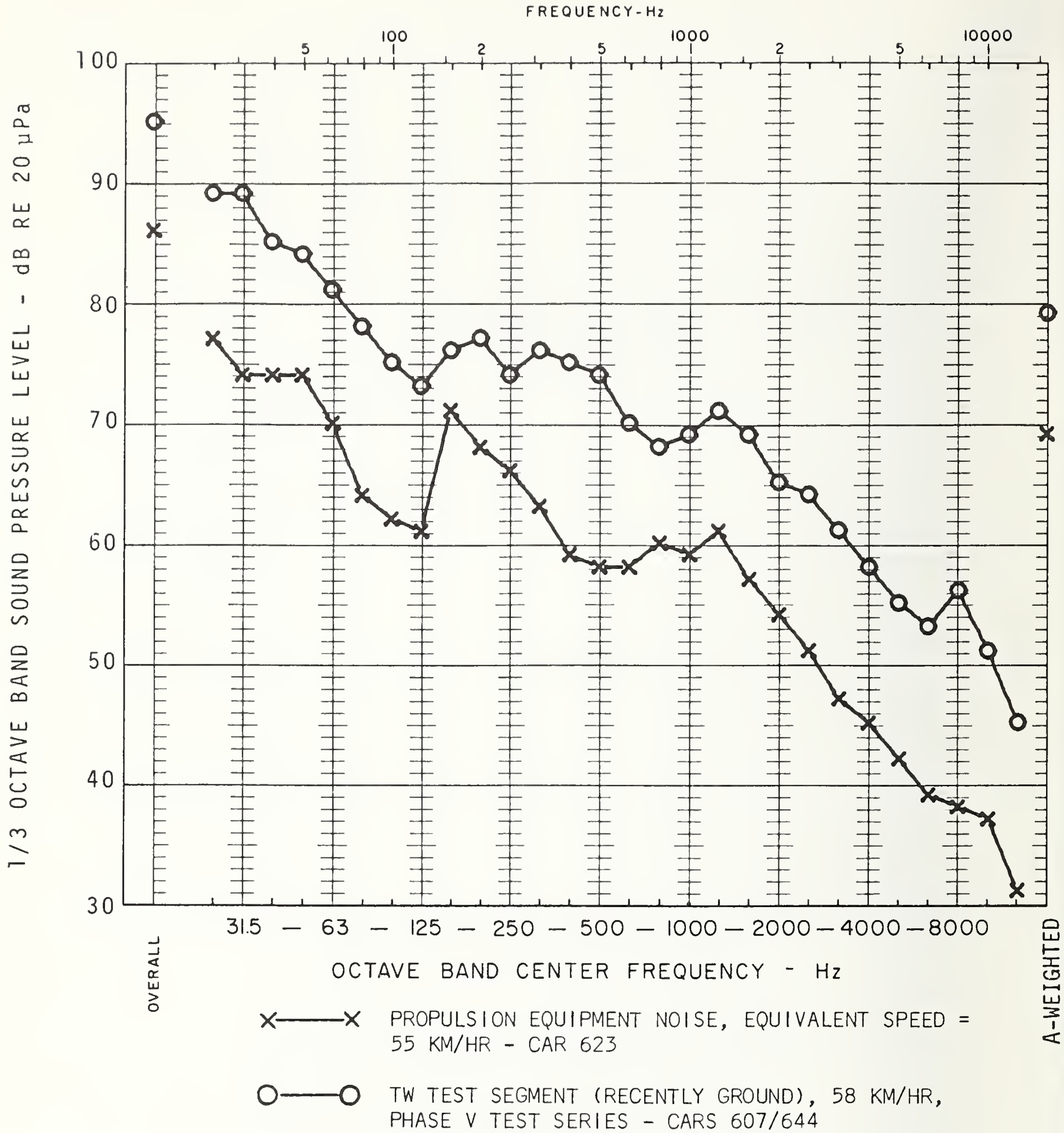


FIGURE 3-6. COMPARISON OF SPECTRA OF PROPULSION EQUIPMENT NOISE AND TYPICAL TEST EXAMPLE - CAR INTERIOR

As shown in Figure 3-6 the overall interior noise is significantly above the propulsion equipment noise over the entire frequency spectrum. (For the specific examples shown in Figure 3-6 the difference is approximately 10 dB.) This indicates that significant reductions of wheel/rail noise can be observed in the car interior, or that the overall noise is dominated by sources other than wheel/rail noise or propulsion equipment noise, e.g., wind noise.

The main conclusions to be drawn are that the propulsion noise is highly dependent on car speed and, therefore, can be a significant or, in some cases, the major part of the total noise at high speed. The data also show that greater reductions of wayside wheel/rail noise could be observed with the married pair cars. Unfortunately, during the planning stages of the program there was no information indicating that the two types of cars had different propulsion systems. Therefore, in selecting the cars to be used for the testing, single car units were selected because of the ability to continue testing with a single car should one car of a 2-car set not be useable at some point during the program.

4. WAYSIDE AND CAR INTERIOR NOISE TEST RESULTS

The analyses of the wayside and car interior noise measurements of Phases IV, V, VI and VII are presented in this section. The procedures for the acoustic data analysis are presented in detail in Interim Report #3 and are not repeated herein. For the car interior noise the measurements consisted of determining the relatively steady noise level observed in the car as the trains pass over the Control Segment and Test Segment for each test track. The data reported are the average of the levels in the center of the car and over one truck. The wayside noise data consists of the average maximum level which occurs during the passby of each train on either the Control or Test Segments of the test tracks.

The testing included four test trains as follows:

a. Cars 613/623 - standard (conventional solid steel) wheels worn by a total of approximately two years of revenue service prior to the testing of Phase IV - the original worn standard wheel train, referred to as "Worn Standard" in the tables.

b. Cars 755/756 - a set of standard steel wheels that were worn by approximately twelve months of revenue service prior to the Phase IV testing - the original new standard wheel train, referred to as "New Standard" in the tables.

c. Cars 607/644 - a 2-car set of standard wheels with grooves on the field side for ring-dampers. The wheels on this train were new at the start of Phase IV - this train is referred to as "Grooved #1" in the tables.

d. Car 606 - a single car with grooves for ring-dampers on the field and flange sides. This train was included in the Phase VII tests only. The wheels on this car were new at the time of the tests. The train is referred to as "Grooved #2" in the tables.

In all of the tests with wheels grooved for ring-dampers, tests were performed both with the damping rings in and with the damping rings out to provide direct comparisons of the effects of the ring-dampers.

All of the testing, wheel truing, rail grinding, and other actions that have been performed in this study are summarized in Table 4-1. This table provides an overview of the entire test program. For simplicity the tests in July 1977 and before, Phases I, II and III, are referred to as Test Series 1 and the tests of October 1977 and later, Phases IV, V, VI and VII, are referred to as Test Series 2. This report presents data from Test Series 2, the data from Test Series 1 having been presented in Interim Report #3. Table 4-2 presents a tabulation of the number of passbys for which acoustical data were recorded for each of the test conditions in Test Series 2.

The average A-weighted sound level results for each test condition of each test phase of Test Series 2 are presented in Tables 4-3 through 4-9. For the wheel squeal tests on the TURN test track direct averages of the A-weighted levels are presented. For the tangent track data, the levels for each test condition are normalized to 60 km/hr assuming that the A-weighted sound level is proportional to 30*log* (speed). The average normlized results are presented in Tables 4-5 through 4-9. Because there are a large number of data points for each test condition, it is necessary to do a considerable amount of averaging to simplify the data to the point where the effects of the noise reduction treatments can be identified. The data in Tables 4-3 through 4-9 are presented to allow the reader to duplicate the analysis of this report or to perform different analyses than presented herein. In addition, all of the unnormalized A-weighted levels and train speeds for each test condition are presented in Appendix A.

The data (Tables 4-3 through 4-9) have been combined to determine overall average levels for each combination of the test parameters that were included in the study. The combined averages are presented in Tables 4-10 through 4-13. As an example of the combined averages, in Phases IV and V the wheels on the worn wheel train had approximately 28 months of wear and the Control Segment of the TW test track had been in service 24 months since last being ground. Hence, the controlled test parameters with the worn standard wheel train at the Control Segment of the TW track were essentially identical in Phases IV and V. Referring to Table 4-5, the data show that the average wayside levels with these wheel and wear conditions were 86.4 and 85.9 dBA for Phases IV and V, respectively, giving a combined average of 86.2 dBA. The level of 86.2 dBA is presented in Table 4-11, for the Test Series 2 wayside results with standard wheels worn 28 months and tangent welded rail worn 24 months.

Tables 4-10 through 4-13 present the overall average levels for the various combinations considering both the Test Series 1 and 2 test parameters. The test parameters include: type of track construction, wheel type, wheel wear since the wheels were new or since the wheels were last trued, and rail wear since the rails had been ground. These combined average levels are used in the following subsections to identify the effects of the noise control treatments. To aid in the interpretation and discussion of the noise control results, the combined averages of Tables 4-10 through 4-14 are also presented graphically in Figures 4-18 through 4-21 of Section 4.1.

Note that the averages of Tables 4-10 through 4-13 incorporate all the data from Test Series 1 and 2. There are some small differences between the combined averages for Test Series 1 used in this report and those used in the previous interim report, Interim Report #3. This is because the data from Phase III were not included in the averages of the previous report, but they are included in the averages of this report. This change does not result in any significant changes in the combined averages.

The following subsections present a discussion and analysis of the results of this program regarding each of the noise control procedures as observed in Test Series 2. Most of the results are discussed in terms of the normalized levels, except for Section 4.1 which presents and discusses the observed sound levels as a function of train speed. Although most of the discussion in Sections 4.2 through 4.4 is in terms of the normalized sound levels, the charts of sound level as a function of speed contribute to the understanding and interpretation of the test data and are referred to in the discussions of the effects of the test parameters.

In addition to the discussion of the effects of the noise control treatments, Section 4.5 presents and discusses the "extra wayside" measurements of Phase IC. In Phase IC measurements were made at the Test Segment of the TW test track at distances of both 7.5 m and 15 m from the track centerline. Comparison of the 15 m and 7.5 m measurement results provides a basis for extrapolating the 7.5 m measurement results to greater distances.

TABLE 4-1. OUTLINE OF TESTING, TRACK MAINTENANCE AND WHEEL TRUING FOR THE WAYSIDE AND CAR INTERIOR NOISE TESTS

Test Phase	Test Date	Description
TEST SERIES 1		
--	April 12, 1976	Tested worn standard wheel train on-blocks for propulsion equipment noise and on TW test track for overall wayside noise.
lA	July 14-15, 1976	Tested worn standard and new standard wheel trains on the TW, TJ and TURN test tracks.
--	July 26-Aug. 13, 1976	Entire Turnaround and TW test tracks ground with rail grinder. TJ test track Segment B joint bars changed.
IB	Aug. 17-19, 1976	Tested the worn standard and new standard wheels on the TW, TJ, TURN and SUB 1, 2 and 3 test tracks. Tested new standard wheel train on-blocks for propulsion equipment noise.
--	Aug. 23-27, 1976	Trued new standard wheels.
IC	Sept. 1-2, 1976	Tested the worn standard and trued new standard wheels on the TW and TURN test tracks.
--	Sept. 24, 1978	Completed installation of wheels on all three resilient wheel trains.

TABLE 4-1. (CONT.)

Test Phase	Test Date	Description
IIA	Oct. 2-4, 1976	Tested all 3 resilient wheel trains on all test tracks, the worn-standard on TJ and TW, and trued-new standard on TW, TJ and TURN.
--	Oct. 12-13, 1976	TJ and SUB 1, 2 and 3 test tracks ground with rail grinders.
IIB	Oct. 14-15, 1976	Tested all five test trains on the TJ, SUB 1, 2 and 3, FROG and ELESTN test tracks.
--		9 months wear period with all trains operating in revenue service. Failure of some resilient wheels occurred during this period.
III	July 14, 1977	Tested worn standard, new standard and remaining resilient wheel trains for interior noise on the TURN, TW, TJ, SUB 1 and SUB 2 test tracks and for wayside noise on the TW and TURN test tracks. Also tested the worn standard wheel train and a resilient wheel train with ventilation dampers both open and closed on the TURN, TW, TJ, SUB 1 and SUB 2 test tracks.

TABLE 4-1. (CONT.)

Test Phase	Test Date	Description
TEST SERIES 2		
--	October 1976 to November 1977	13 month wear period. All resilient wheels removed from service.
--	November 1977	Installed 2-car set of ring-damped wheels - rings on field side.
IV	Nov. 8-10, 1977	Tested worn standard, new standard and ring-damped wheels with rings in and rings out on the TURN, TW, TJ, SUB 1 and SUB 2 test track.
--		Ground rails of test Segments of the TW, TJ and TURN test tracks and SUB 1 and SUB 2 test tracks.
V	Dec. 6-7, 1977	Tested worn standard, new standard and ring-damped wheels with rings in and rings out on the TURN, TW, TJ, SUB 1 and SUB 2 test track. Measured propulsion equipment with all three trains on blocks.
--		Trued wheels on all three test trains.
VI	Dec. 9, 1977	Tested worn standard, new standard and ring-damped wheels with rings in and rings out on the TURN, TW and TJ test tracks. The TJ tests were car interior noise only.

TABLE 4-1. (CONT.)

Test Phase	Test Date	Description
--		Installed a second set of ring-damped wheels grooved for rings on both the field and flange side of the wheels.
VII	Sept. 19, 1978	Tested both sets of ring-damped wheels with rings in and rings out on the TURN test track. The second set of wheels was tested with the rings on the field side, the flange side, and on both the field and the flange side.

TABLE 4-2. LISTING OF NUMBER OF TEST RUNS FOR EACH TEST CONDITION OF SERIES 2

Test Phase and Track	TRAIN							
	Worn	New	Damped #1		Damped #2			
			Rings In	Rings Out	Field	Rings In Flange	Both	Rings Out
PHASE IV								
Welded-TW	5	9	3	4	--	--	--	--
Jointed-TJ	5	9	3	4	--	--	--	--
Welded-SUB 1	4	4	3	4	--	--	--	--
Jointed-SUB 2	4	4	3	4	--	--	--	--
Curve-TURN	4	7	4	4	--	--	--	--
PHASE V								
Welded-TW	4	5	4	4	--	--	--	--
Jointed-TJ	4	5	4	4	--	--	--	--
Welded-SUB 1	4	4	4	4	--	--	--	--
Jointed-SUB 2	4	4	4	4	--	--	--	--
Curve-TURN	4	4	4	4	--	--	--	--
PHASE VI								
Welded-TW	4	5	4	4	--	--	--	--
Jointed-TJ	4	5	4	4	--	--	--	--
Curve-TURN	4	5	4	4	--	--	--	--
PHASE VII								
Curve-TURN	--	--	12 2-Car 6 1-Car	6 2-Car 6 1-Car	6 1-Car	6 1-Car	6 1-Car	6 1-Car

TABLE 4-3a. AVERAGE SOUND LEVELS - L_A - dBA
WAYSIDE NOISE - TURN TEST TRACK:
PHASES IV, V AND VI

Test Phase	Turn Track	Train			
		Worn Standard 613/623	New Standard 755/756	Grooved - Rings Out 607/644	Grooved - Rings In 607/644
IV Worn Rails and Wheels	Control	98.7 *(2.7)	95.4 (3.3)	89.2 (3.3)	77.8 (1.1)
	Test	100.1 (2.0)	98.8 (3.1)	96.6 (3.4)	83.6 (6.8)
	AVG.	99.4	97.1	92.9	80.7
V Ground Rail and Worn Wheels	Control	93.8 (5.0)	93.7 (2.2)	86 (1.2)	79.8 (2.5
	Test	91.6 (2.5)	91.8 (5.6)	87.1 (2.1)	75.8 (0.6)
	AVG.	92.6	92.8	86.5	77.8
VI Ground Rail and Trued Wheels	Control	91.2 (0.7)	90.8 (3.3)	90.5 (3.0)	80.8 (0.7)
	Test	87.6 (1.7)	91.1 (4.4)	85.5 (1.5)	77.8 (0.8)
	AVG.	89.4	91.0	88.0	79.3

*Numbers in parentheses () are the data standard deviations.

TABLE 4-3b. AVERAGE SOUND LEVELS - L_A - dBA
WAYSIDE NOISE - TURN TEST TRACK:
PHASE VII

Train	Damping Rings	Track Segment		
		Control	Test	Average
606	Both	76.1 *(0.5)	76.1 (0.7)	76.1
606	Inside	76.5 (0.4)	78.0 (1.0)	77.2
606	Field	76.0 (0.5)	76.1 (1.7)	76.0
606	Out	78.3 (1.8)	80.4 (2.6)	79.4
607/644	In-Frozen	84.9 (3.0)	80.4 (1.4)	82.6
607/644	In-New	77.3 (1.3)	76.4 (0.9)	76.8
607	In-New	79.5 (2.0)	77.1 (1.1)	78.3
607/644	Out	86.4 (3.6)	84.0 (2.6)	85.2
607	Out	93.3 (2.9)	81.9 (1.0)	87.6

*Numbers in parentheses () are the data standard deviations.

TABLE 4-4. AVERAGE SOUND LEVELS - L_A - dBA CAR INTERIOR NOISE - TURN TEST TRACK

Test Phase	Turn Track	Train: Worn Standard 613/623	Train: New Standard 755/756	Train: Grooved - Rings Out 607/644	Train: Grooved - Rings In 607/644
IV Worn Rails and Wheels	Control	77.7 *(0.9)	77.8 (2.4)	74.6 (1.0)	72.6 (1.1)
	Test	80.7 (2.6)	81.3 (3.6)	81.3 (1.0)	75.1 (2.4)
	AVG.	79.2	79.6	78.0	73.8
V Ground Rail and Worn Wheels	Control	77.5 (1.5)	84.0 (2.5)	74.4 (0.6)	74.4 (1.3)
	Test	75.9 (1.9)	78.1 (2.8)	75.1 (0.9)	72.6 (0.4)
	AVG.	76.7	81.0	74.8	73.5
VI Ground Rail and Trued Wheels	Control	73.7 (0.7)	74.8 (0.5)	76.6 (0.8)	72.6 (0.5)
	Test	75.6 (0.3)	76.6 (1.2)	74.8 (0.5)	74.5 (0.5)
	AVG.	74.6	75.4	75.7	73.6

*Numbers in parentheses () are the data standard deviations.

TABLE 4-5. AVERAGE NORMALIZED SOUND LEVELS - L'_A - dBA
WAYSIDE NOISE - TW TEST TRACK

Test Phase	Turn Track	Train			
		Worn Standard 613/623	New Standard 755/756	Grooved - Rings Out 607/644	Grooved - Rings In 607/644
IV Worn Rails and Wheels	Control	86.4 *(0.3)	86.7 (0.9)	83.7 (0.8)	83.5 (0.4)
	Test	86.5 (0.4)	86.4 (0.5)	83.3 (0.3)	--
	AVG.	86.4	86.6	83.5	--
V Ground Rail and Worn Wheels	Control	85.9 (1.1)	85.7 (0.7)	83.6 (1.1)	82.8 (0.3)
	Test	85.8 (0.8)	85.0 (1.3)	82.2 (0.2)	82.0 (0.2)
	AVG.	85.8	85.3	82.9	82.4
VI Ground Rail and Trued Wheels	Control	89.2 (0.5)	90.3 (0.8)	87.3 (0.4)	87.4 (0.2)
	Test	85.4 (0.7)	87.2 (0.3)	83.2 (0.4)	83.8 (0.4)
	AVG.	87.3	88.8	85.2	85.6

*Numbers in parentheses () are the data standard deviations.

TABLE 4-6. AVERAGE NORMALIZED SOUND LEVELS - L'_A - dBA
CAR INTERIOR NOISE - TW TEST TRACK

Test Phase	Test Segment	Train			
		Worn Standard 613/623	New Standard 755/756	Grooved - Rings Out 607/744	Grooved - Rings In 607/644
IV Worn Rails and Wheels	Control	80.2 *(0.3)	79.6 (0.9)	77.0 (0.2)	77.9 (0.5)
	Test	80.7 (0.1)	80.0 (1.0)	77.4 (0.4)	79.0 (0.6)
	AVG.	80.4	79.8	77.2	78.4
V Ground Rail and Worn Wheels	Control	79.6 (0.6)	78.2 (0.5)	78.9 (0.8)	78.6 (0.4)
	Test	80.2 (0.8)	78.6 (0.4)	79.6 (0.8)	79.2 (0.1)
	AVG.	79.9	78.4	79.2	78.9
VI Ground Rail and Trued Wheels	Control	82.2 (0.9)	83.1 (0.5)	82.0 (0.3)	80.4 (0.2)
	Test	81.8 (0.4)	82.8 (0.8)	81.9 (0.2)	80.7 (0.4)
	AVG.	82.0	83.0	82.0	80.5

*Numbers in parentheses () are the data standard deviations.

TABLE 4-7. AVERAGE NORMALIZED SOUND LEVELS - L'_A - dBA
WAYSIDE NOISE - TJ TEST TRACK

Test Phase	Test Segment	Train			
		Worn Standard 613/623	New Standard 755/756	Grooved - Rings Out 607/644	Grooved - Rings In 607/644
IV Worn Rails and Wheels	Control	88.8 *(0.8)	88.3 (0.9)	87.4 (1.9)	87.5 (1.7)
	A	86.7 (0.4)	87.6 (1.1)	85.3 (0.4)	86.9 (0.6)
	B	87.0 (0.1)	86.1 (1.4)	85.5 (0.6)	86.8 (1.1)
	AVG.	87.5	87.3	86.1	87.1
V Ground Rail and Worn Wheels	Control	92.7 (0.4)	91.7 (0.6)	89.3 (0.4)	89.1 (0.5)
	A	88.1 (0.3)	87.4 (0.5)	85.4 (0.4)	85.7 (0.4)
	B	87.8 (0.5)	86.8 (0.7)	86.6 (0.7)	85.6 (0.6)
	AVG.	89.5	88.6	87.1	86.8

*Numbers in parentheses () are the data standard deviations.

TABLE 4-8. AVERAGE NORMALIZED SOUND LEVELS - L'_A - dBA
CAR INTERIOR NOISE - TJ TEST TRACK

Test Phase	Test Segment	Train			
		Worn Standard 613/623	New Standard 755/756	Grooved - Rings Out 607/644	Grooved - Rings In 607/644
IV Worn Rails and Wheels	Control	83.2 *(0.6)	81.6 (0.7)	82.0 (1.0)	82.9 (0.9)
	A	81.6 (0.4)	80.0 (0.7)	79.5 (0.6)	82.0 (2.0)
	B	82.2 (0.5)	80.5 (0.8)	79.8 (0.3)	81.6 (0.8)
	AVG.	82.3	80.7	80.4	82.2
V Ground Rail and Worn Wheels	Control	83.7 (0.4)	81.4 (0.6)	83.9 (0.3)	83.6 (0.4)
	A	81.2 (0.3)	79.3 (0.3)	81.1 (0.8)	80.8 (0.5)
	B	81.8 (0.3)	79.9 (0.5)	80.6 (0.6)	80.8 (0.6)
	AVG.	82.2	80.2	81.9	81.7
VI Ground Rail and Trued Wheels	Control	84.0 (0.5)	85.0 (0.5)	85.5 (0.2)	84.0 (0.6)
	A	82.7 (0.4)	83.1 (0.2)	82.6 (0.2)	81.5 (0.2)
	B	83.2 (0.8)	84.0 (0.7)	83.4 (0.1)	82.3 (0.3)
	AVG.	83.3	84.0	83.8	82.6

*Numbers in parentheses () are the data standard deviations.

TABLE 4-9. AVERAGE NORMALIZED SOUND LEVELS - L'_A - dBA
CAR INTERIOR NOISE - SUBWAY TEST TRACKS

Test Phase	Test Track	Train			
		Worn Standard 613/623	New Standard 755/756	Grooved - Rings Out 607/644	Grooved - Rings In 607/644
IV Worn Rails and Wheels	Welded [SUB 1]	87.4 *(0.6)	85.4 (1.0)	82.4 (0.2)	85.1 (0.6)
	Jointed [SUB 2]	88.7 (0.7)	84.6 (0.5)	83.2 (0.2)	85.8 (0.8)
V Ground Rail and Worn Wheels	Welded [SUB 1]	86.9 (0.2)	83.0 (0.8)	82.8 (0.6)	82.5 (0.6)
	Jointed [SUB 2]	87.3 (0.3)	83.1 (0.5)	84.2 (0.6)	83.3 (0.8)

*Numbers in parentheses () are the data standard deviations.

TABLE 4-10. COMBINED AVERAGE SOUND LEVELS - dBA - TURN TEST TRACK

Train	Wheel Condition	Wayside		Car Interior	
		Rail Worn	Rail Ground	Rail Worn	Rail Ground
STANDARD WHEELS					
Test Series 1					
New Stnd.	New	85.8	88.2	73.5	75.4
New Stnd.	Trued	--	90.8	--	78.2
New & Worn Stnd.	Worn, 12 Mo.	90.8	92.2	77.9	78.8
Worn Stnd.	Worn, 24 Mo.	90.9	--	76.4	--
Test Series 2					
Grooved #1[1]	New	90.6	87.1	76.8	75.1
Grooved #2[2]	New	78.3	80.4	--	--
Grooved #1, New & Worn Stnd.	Trued	90.8	88.1	75.0	75.7
New Stnd.	Worn, 16 Mo.	96.0	91.8	81.0	78.1
Worn Stnd.	Worn, 28 Mo.	97.5	91.6	78.6	75.9
Grooved #1	Worn, 10 Mo.	89.8	83.0	--	--
RESILIENT WHEELS					
Test Series 1					
Acousta Flex	New	--	79.0	--	75.0
Bochum	New	--	79.2	--	73.3
SAB	New	--	87.5	--	78.8
Acousta Flex	Worn, 9 Mo.	77.6	--	72.8	--
SAB	Worn, 9 Mo.	80.0	--	74.0	--
RING DAMPED WHEELS					
Test Series 2					
Grooved #1[1]	New	80.4	75.8	74.0	72.6
Grooved #2[2]	New	76.2	76.7	--	--
Grooved #1	Trued	80.8	77.8	72.6	74.5
Grooved #1	Worn, 10 Mo.[3]	84.9	80.4	--	--
Grooved #1	Worn, 10 Mo.[4]	78.4	76.8	--	--

[1] Grooved #1 is Cars 607/644 with grooves for ring-dampers on the field side of the wheels.

[2] Grooved #2 is Car 606 with grooves for ring-dampers on both the field and flange sides of the wheels.

[3] Ring-dampers frozen in grooves.

[4] New ring-dampers installed.

TABLE 4-11. COMBINED AVERAGE SOUND LEVELS - L'_A - dBA - TW TEST TRACK

Train	Wheel Condition	Wayside: Rail Worn 24 Mo.	Wayside: Rail Worn 12 Mo.	Wayside: Rail Ground	Car Interior: Rail Worn 24 Mo.	Car Interior: Rail Worn 12 Mo.	Car Interior: Rail Ground
STANDARD WHEELS							
Test Series 1							
New Stnd.	New	--	80.7	81.8	--	74.4	74.6
New Stnd.	Trued[1]	--	83.6	83.4	--	77.3	77.3
New & Worn Stnd.	Worn, 12 Mo.	84.1	83.2	85.2	79.5	79.5	78.8
Worn Stnd.	Worn, 24 Mo.	83.2	83.6	--	77.9	78.4	--
Test Series 2							
Grooved #1	New	83.6	83.3	82.2	78.0	77.4	79.6
New Stnd.	Worn, 16 Mo.	86.2	86.4	85.0	78.9	80.0	78.6
Worn Stnd.	Worn, 28 Mo.	86.2	86.5	85.8	79.9	80.7	80.2
Grooved #1	Trued[1]	87.3	--	83.2	82.0	--	81.9
New Stnd	Trued[2]	90.3	--	87.2	83.1	--	82.8
Worn Stnd.	Trued[3]	89.2	--	85.4	82.2	--	81.8
RESILIENT WHEELS							
Acousta Flex	New	--	83.5	81.5	--	76.5	76.7
Bochum	New	--	83.8	82.4	--	76.2	76.5
SAB	New	--	82.3	81.2	--	75.5	75.8
Acousta Flex	Worn, 9 Mo.	84.2	84.0	--	76.8	76.9	--
SAB	Worn, 9 Mo.	85.7	84.1	--	79.2	78.9	--
RING-DAMPED WHEELS							
Test Series 2							
Grooved #1	New	83.2	--	82.0	78.2	79.0	79.2
Grooved #1	Trued[1]	87.4	--	83.8	80.4	--	80.7

[1] New wheels that have been trued.

[2] Wheels trued after 12 months wear.

[3] Wheels trued after 24 months wear.

TABLE 4-12. COMBINED AVERAGE SOUND LEVELS - L'_A - dBA - TJ TEST TRACK

Train	Wheel Condition	Wayside: Rail Worn 24 Mo.	Wayside: Rail Worn 12 Mo.	Wayside: Aligned Joints	Wayside: Rail Ground	Car Interior: Rail Worn 24 Mo.	Car Interior: Rail Worn 12 Mo.	Car Interior: Aligned Joints	Car Interior: Rail Ground
STANDARD WHEELS									
Test Series 1									
New Stnd.	New	--	88.2	86.4	--	--	78.4	77.6	--
New Stnd.	Trued[1]	--	88.7	88.3	85.6	--	80.9	80.3	80.1
New & Worn Stnd.	Worn, 12 Mo.	--	89.6	89.3	88.0	80.9	81.5	80.6	80.5
Worn Stnd.	Worn, 24 Mo.	--	--	--	--	82.0	80.4	--	--
Test Series 2									
Grooved #1	New	88.4	85.4	--	85.0	83.0	79.6	--	80.8
New Stnd.	Worn, 16 Mo.	90.0	86.8	--	87.1	81.5	80.2	--	79.6
Worn Stnd.	Worn, 28 Mo.	90.8	87.2	--	88.0	83.4	81.9	--	81.5
Grooved #1	Trued[1]	--	--	--	--	85.5	--	--	81.9
New Stnd.	Trued[2]	--	--	--	--	85.0	--	--	83.6
Worn Stnd.	Trued[3]	--	--	--	--	84.0	--	--	83.0
RESILIENT WHEELS									
Test Series 1									
Acousta Flex	New	--	87.4	85.4	84.0	--	80.9	80.8	78.6
Bochum	New	--	87.6	86.7	83.6	--	80.6	79.5	79.0
SAB	New	--	88.6	87.6	84.8	--	81.0	80.2	79.2
Acousta Flex	Worn, 9 Mo.	--	--	--	--	80.7	78.7	--	--
SAB	Worn, 9 Mo.	--	--	--	--	80.8	79.4	--	--
RING-DAMPED									
Test Series 2									
Grooved #1	New	88.3	86.8	--	85.6	83.2	81.8	--	80.8
Grooved #1	Trued[1]	--	--	--	--	84.0	--	--	83.0

[1] New wheels that have been trued.

[2] Wheels trued after 12 months wear.

[3] Wheels trued after 24 months wear.

TABLE 4-13. COMBINED AVERAGE SOUND LEVELS - L'_A - dBA - SUBWAY TEST TRACKS

Train	Wheel Condition	Welded Rail: Rail Worn 12 Mo.	Welded Rail: Rail Worn 9 Mo.	Welded Rail: Rail Ground	Jointed Rail: Rail Worn 12 Mo.	Jointed Rail: Rail Worn 9 Mo.	Jointed Rail: Rail Ground
STANDARD WHEELS							
Test Series 1							
New Stnd.	New	82.5[1]	--	--	84.8[1]	--	--
New Stnd.	Trued	--	--	81.0	--	--	82.3
Worn Stnd.	Worn, 12 Mo.	85.3[1]	--	85.2	86.7[1]	--	87.1
Worn Stnd.	Worn, 24 Mo.	--	84.8	--	--	87.0	--
Test Series 2							
Grooved #1	New	82.4	--	82.5	83.2	--	84.2
New Stnd.	Worn, 16 Mo.	85.4	--	83.0	84.6	--	83.1
Worn Stnd.	Worn, 28 Mo.	87.4	--	86.9	88.7	--	87.3
RESILIENT WHEELS							
Acousta Flex	New	82.6	--	79.4	84.1	--	81.3
Bochum	New	82.1	--	79.2	83.7	--	80.9
SAB	New	80.9	--	80.1	84.1	--	81.9
Acousta Flex	Worn, 9 Mo.	--	83.1	--	--	86.1	--
RING-DAMPED WHEELS							
Test Series 2							
Grooved #1	New	85.1	--	82.8	85.8	--	83.3

[1]Adjustment added due to apparent closed vents - adjustments based on Phase III tests with vents open and closed.

4.1 SOUND LEVEL AS A FUNCTION OF TRAIN SPEED

Figures 4-1 through 4-17 present as a function of speed the A-weighted sound level results for the Phase IV, V and VI tangent track tests. The data on these charts have been arranged to reflect the variations of sound level as a function of wheel and rail condition and train speed. In addition, the charts present direct comparisons of the sound level with and without the ring dampers installed in the grooved wheel trains.

The best fit lines for various data groups are shown on Figures 4-1 through 4-17. The best fit lines on these figures have a speed dependence ranging from a low of $18\,log$ V to a high of $40\,log$ V with most of the data showing a speed dependence close to $30\,log$ V. The fact that the slopes of the best fit lines are all reasonably close to 30 confirms that using the normalized levels, L_A', to make direct comparisons of the various test conditions is an appropriate procedure. Of course, if the typical slopes were consistently different from 30, direct comparisons of the normalized values could lead to invalid conclusions. The average normalized values for each of the data sets in Figures 4-1 to 4-17 closely agree with the values of the best fit lines at 60 km/hr. In most cases the variation between the two is insignificant, the greatest variation being about 0.3 dBA. This is further confirmation that the values of L_A' can be used to evaluate the test results.

Following is a brief discussion of the data presented in Figures 4-1 through 4-17 with respect to the effects that the various noise control treatments had on the overall noise levels.

Tangent Welded Test Track

Figures 4-1 through 4-4 present the wayside sound levels at the TW test track. Figure 4-1 compares worn and new wheels on worn and ground rails. The "worn wheel" category includes two test trains, first the train with new steel wheels at the start of this study and second the train with standard wheels that had been in service approximately one year at the start of the study. At the start of Test Series 2 these wheels had been in revenue service approximately one and two years, respectively. The "worn rail" category of Figures 4-1 through 4-4 includes the Test Segment before grinding and the Control Segment with two years of wear. In Phase IV, the Test Segment had been in service approximately one year since the rail grinding of Phase I.

The data on Figure 4-1 clusters very closely about the best fit lines. The graph indicates:

- New wheels on ground rails are quietest.
- New wheels on work rails produce consistently 1 dBA higher noise levels.
- Worn wheels on ground rails result in higher sound levels than new wheels on either worn or ground rails. This difference appears to be speed dependent. The difference is 0 to 1 dBA, below about 50 km/hr while at 80 km/hr the difference is 4 to 5 dBA.
- Worn wheels on worn rails result in the highest wayside noise levels. Compared to the quietest condition (new wheels, ground track) the levels average 3 dBA higher at 40 km/hr and 5 dBA at 80 km/hr.

Figure 4-2 compares the wayside levels at the TW test track with new and trued wheels. The data show the trued wheels resulted in significantly higher noise levels on worn rails and only slightly higher levels on recently ground rails.

Figures 4-3 and 4-4 compare the wayside noise levels at the TW test track with and without the damping rings installed in the Grooved #1 train. Figure 4-3 presents the results on ground rails and Figure 4-4 presents the results on worn rails. These figures show that the ring-dampers did not have an identifiable effect on the wayside noise levels and show similar comparisons for the other variables as appear on Figures 4-1 and 4-2.

Figures 4-5 through 4-8 present the car interior sound level results at the TW test track. Figure 4-5 shows that only small differences resulted with new versus worn wheels and ground versus worn rails. However, as shown on Figure 4-6, truing the wheels resulted in higher sound levels, 3 to 4 dBA higher, on both ground and worn rails. Figures 4-7 and 4-8 compare the car interior sound level results with and without ring-dampers. The data do not indicate significant reduction of car interior sound levels with ring-dampers for operation on tangent welded track.

Tangent Jointed Test Track

Figures 4-9 through 4-11 present the wayside data from the TJ test track. It is of interest that these data show a speed dependence of approximately $25 \log V$, consistently lower than the $30 \log V$ found to be typical for most other test conditions. The TJ wayside data on Figure 4-9 show that the rail with two years of revenue service since being ground had significantly higher sound levels than the rail with only one year of service since grinding. In addition, the data for the worn wheels on rail worn two years is not well clustered about the best fit line; the data points range about ±3 dBA from the line. For most other data sets the range is ±1 to 2 dBA.

The worn rail data for two years wear presented in Figure 4-9 is repeated in Figure 4-10 to provide a reference for comparison of ground rail, rail worn one year, and rail worn two years (using both figures). The comparison shows that the rail with one year of wear and ground rail resulted in essentially equivalent sound levels, while the rail with two years of wear resulted in significantly higher sound levels. The charts also provide an interesting comparison of worn and new wheels. On the ground rails and the rails worn one year the new wheels were an average of 1 to 1.5 dBA quieter than the worn wheels while on the rails worn two years the levels averaged 2 to 2.5 dBA quieter with the new wheels. This is an indication that the effects of grinding and wheel smoothing are not directly additive.

Figure 4-11 provides a comparison of the wayside test results at the TJ test track with and without ring-dampers installed in new grooved wheels. As at the other tangent test tracks, the ring-dampers did not result in identifiable noise reductions.

Figure 4-12 through 4-15 present the car interior sound level data for the tests on the TJ test track. The data show the car interior sound levels on the test track with rail worn two years averaged 1 to 2 dBA higher than on the test track with rails worn one year or on the test track with ground rails. Figure 4-14 shows that ring-dampers did not have a significant influence on the car interior sound levels.

Figure 4-15 shows the comparison of the sound levels before and after truing the wheels. This chart includes the data with the new grooved wheels (Grooved #1) before and after truing. As is evident the average car interior sound levels with the trued wheels were 1 to 3 dBA higher than with the new wheels. The same change in sound level was observed at the worn and ground test track sections. As discussed in subsequent sections, the increases in noise level were observed after truing both the worn wheels and the new wheels. This was apparently caused by the wheels being tested almost immediately after truing. The cutter marks from the milling tool were still clearly visible and could have caused the higher noise levels.

Subway Test Tracks

The data from the tangent welded and jointed subway test tracks is presented in Figures 4-16 and 4-17. The data show the ground rail to be slightly quieter than the worn rail, the new wheels to be 0 to 3 dBA quieter than the worn wheels and essentially no difference in sound level with the damping rings in or the damping rings out of the grooved wheels.

Figures 4-18, 4-19, 4-20 and 4-21 present data showing the average noise levels for various test conditions on the TW, TJ, SUB and TURN test tracks. The charts include data for the standard and ring-damped wheels.

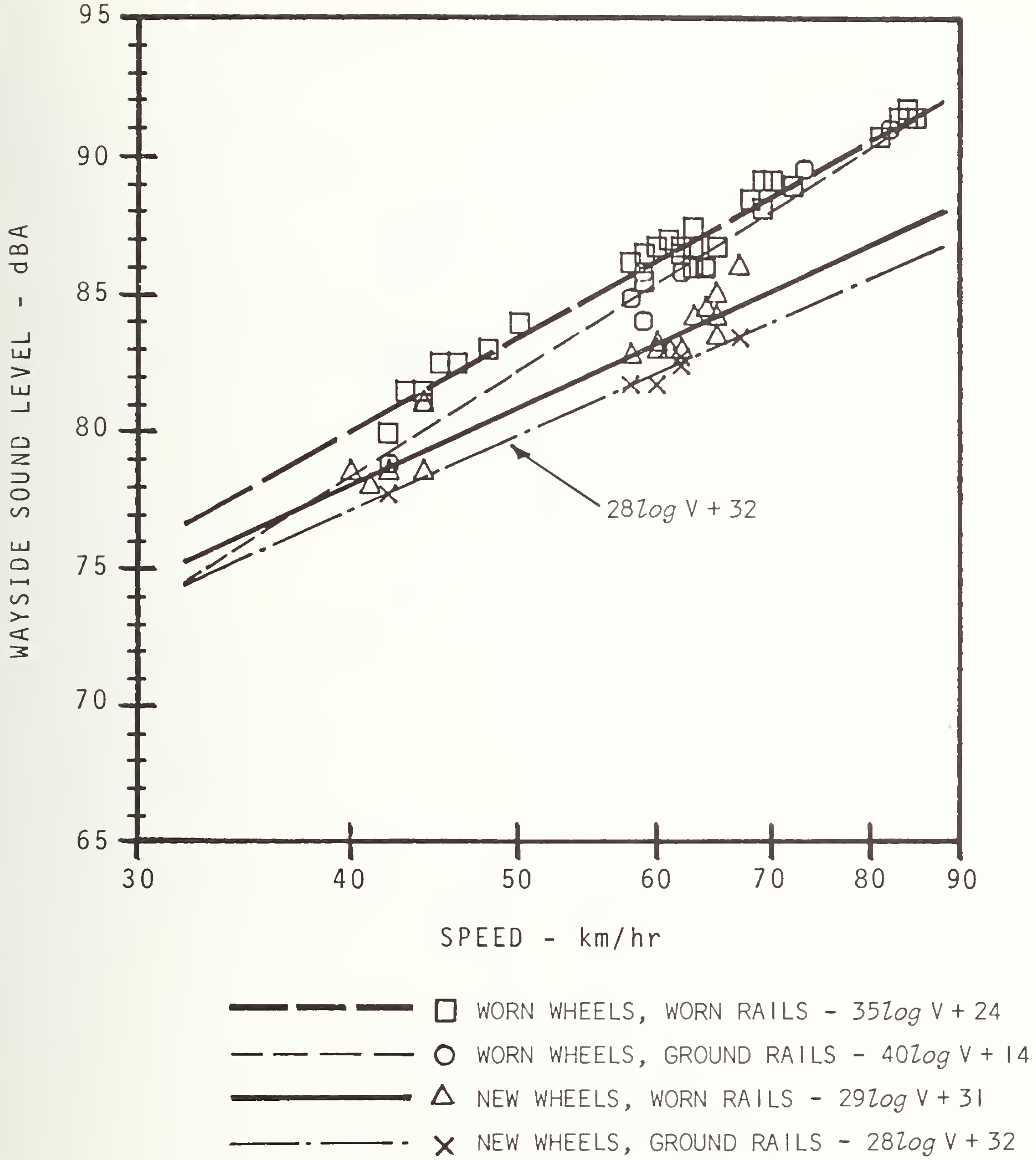


FIGURE 4-1. WAYSIDE SOUND LEVELS AT TW TEST TRACK WITH NEW AND WORN WHEELS AND WITH WORN AND GROUND RAIL

TEST SERIES 2 - 7.5 m FROM TRACK CENTERLINE

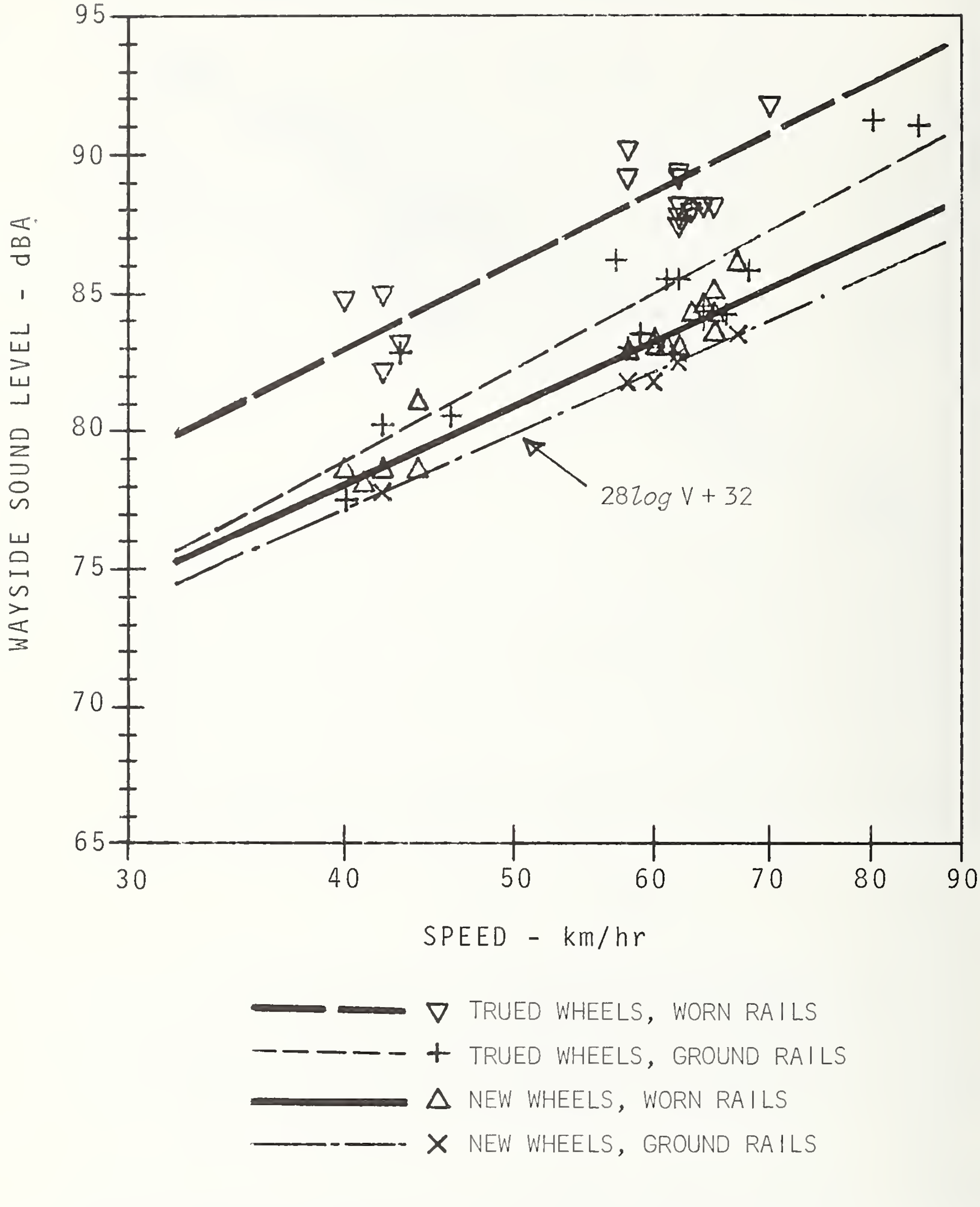


FIGURE 4-2. WAYSIDE SOUND LEVELS AT TW TEST TRACK WITH NEW AND TRUED WHEELS AND WITH WORN AND GROUND RAILS

7.5 m FROM TRACK CENTERLINE

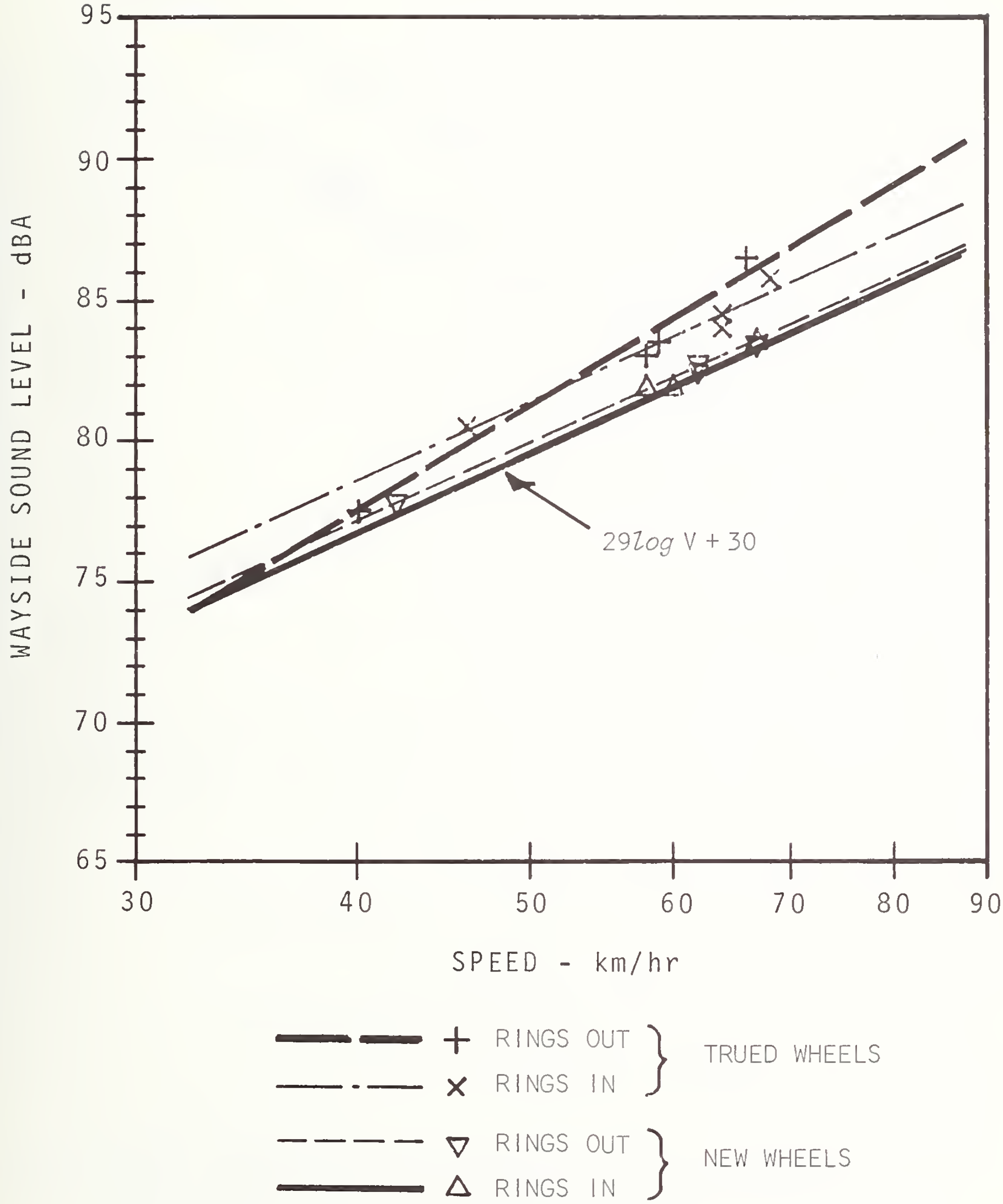


FIGURE 4-3. WAYSIDE SOUND LEVELS WITH AND WITHOUT RING RING DAMPERS, GROUND TANGENT WELDED TRACK, NEW AND TRUED GROOVED WHEELS

7.5 m FROM TRACK CENTERLINE

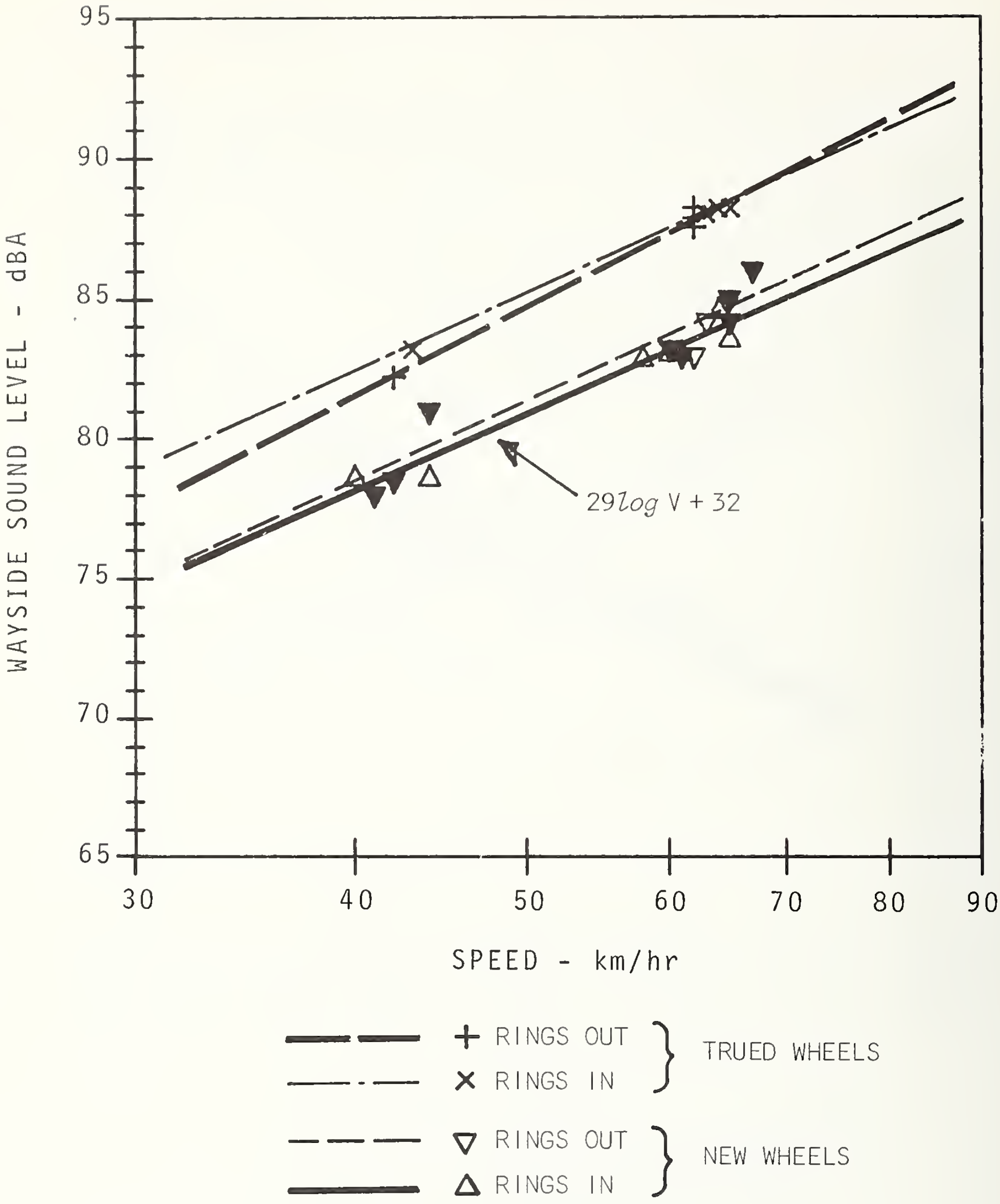


FIGURE 4-4. WAYSIDE SOUND LEVELS WITH AND WITHOUT RING DAMPERS, WORN TANGENT WELDED TRACK, NEW AND TRUED GROOVED WHEELS

7.5 m FROM TRACK CENTERLINE

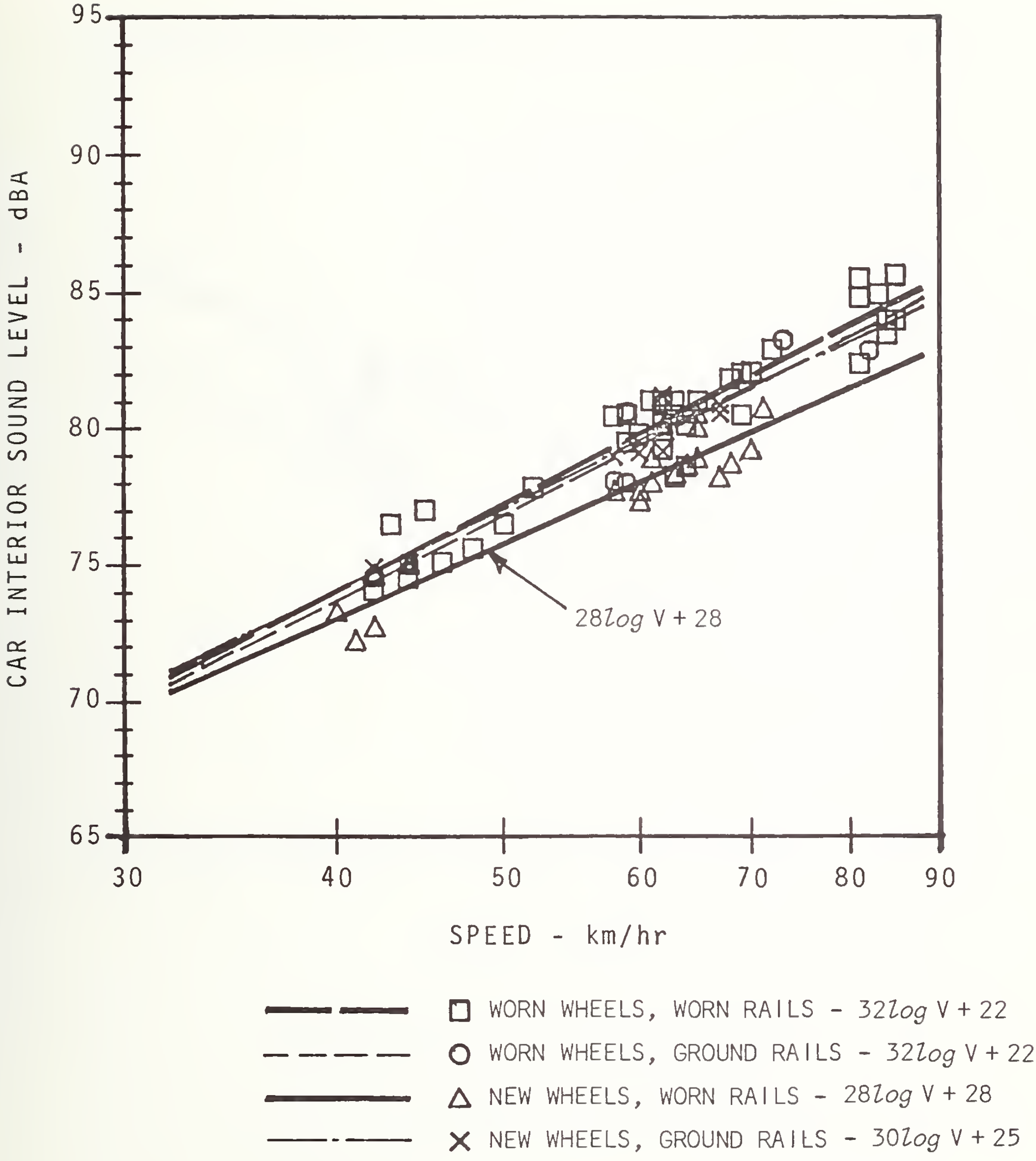


FIGURE 4-5. CAR INTERIOR SOUND LEVELS ON TW TEST TRACK WITH NEW AND WORN WHEELS AND WITH WORN AND GROUND RAILS - TEST SERIES 2

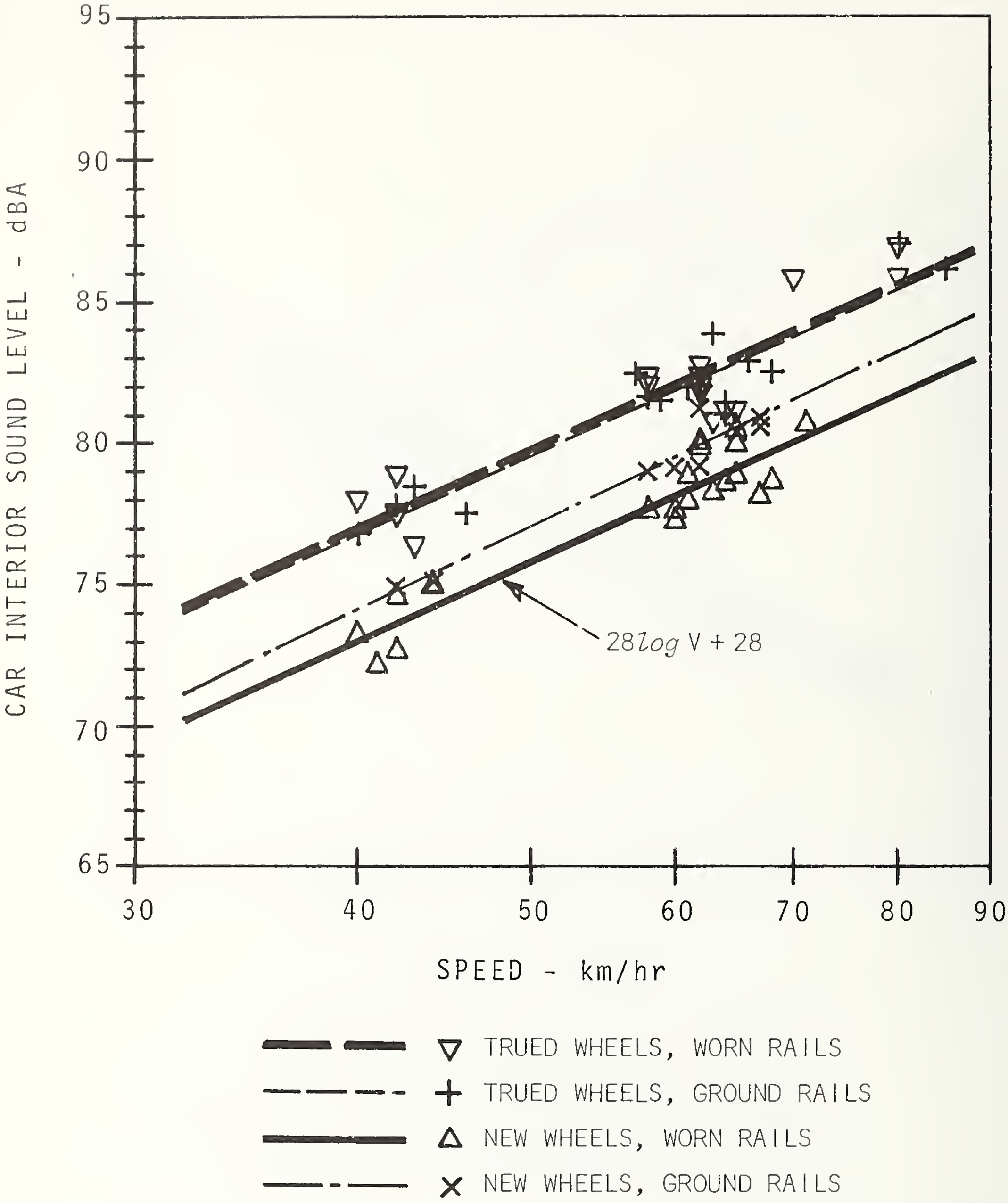


FIGURE 4-6. CAR INTERIOR SOUND LEVELS ON TW TEST TRACK WITH NEW AND TRUED WHEELS WITH WORN AND GROUND RAILS

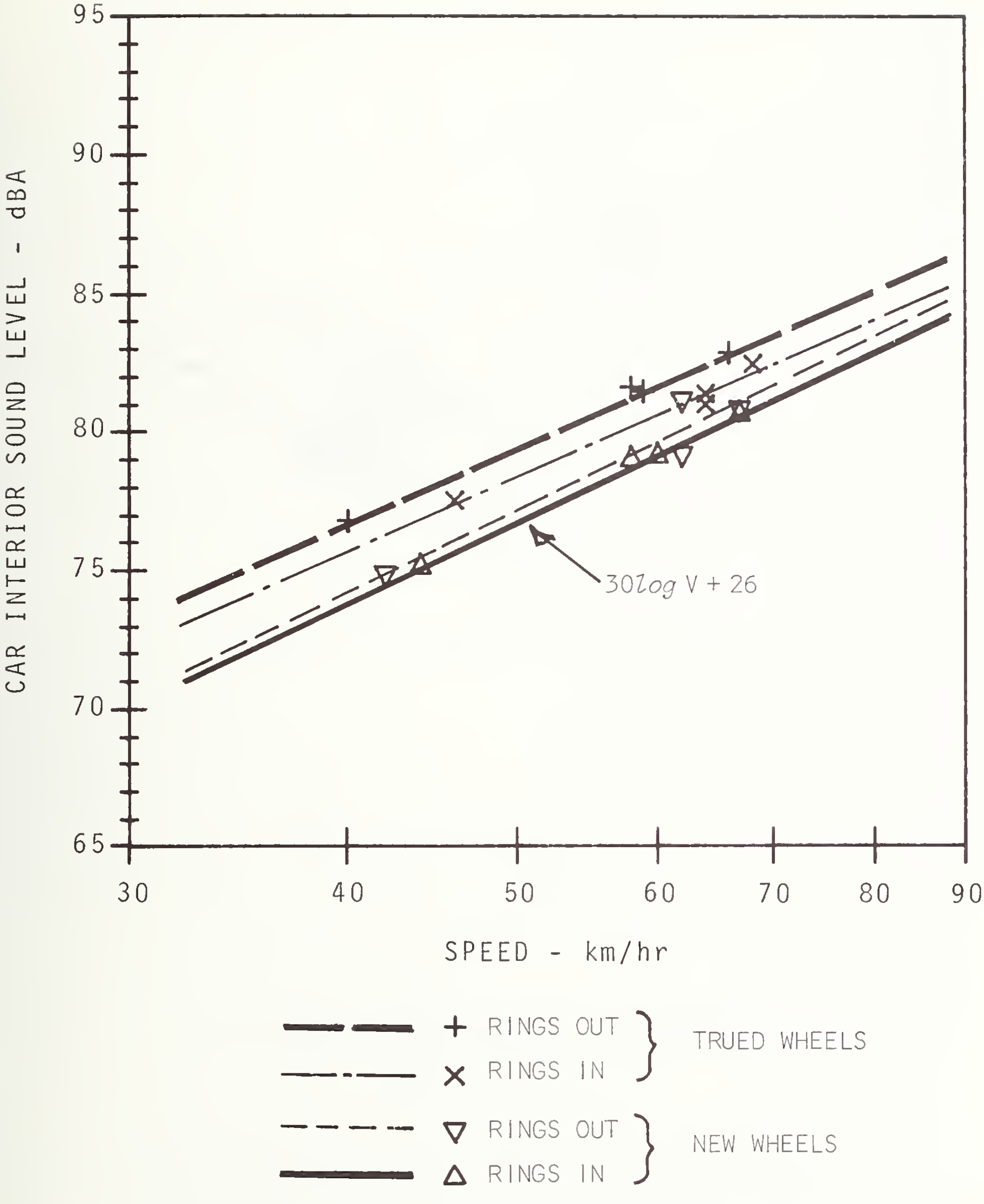


FIGURE 4-7. CAR INTERIOR SOUND LEVELS WITH AND WITHOUT RING DAMPERS, GROUND TANGENT WELDED TRACK, NEW AND TRUED GROOVED WHEELS

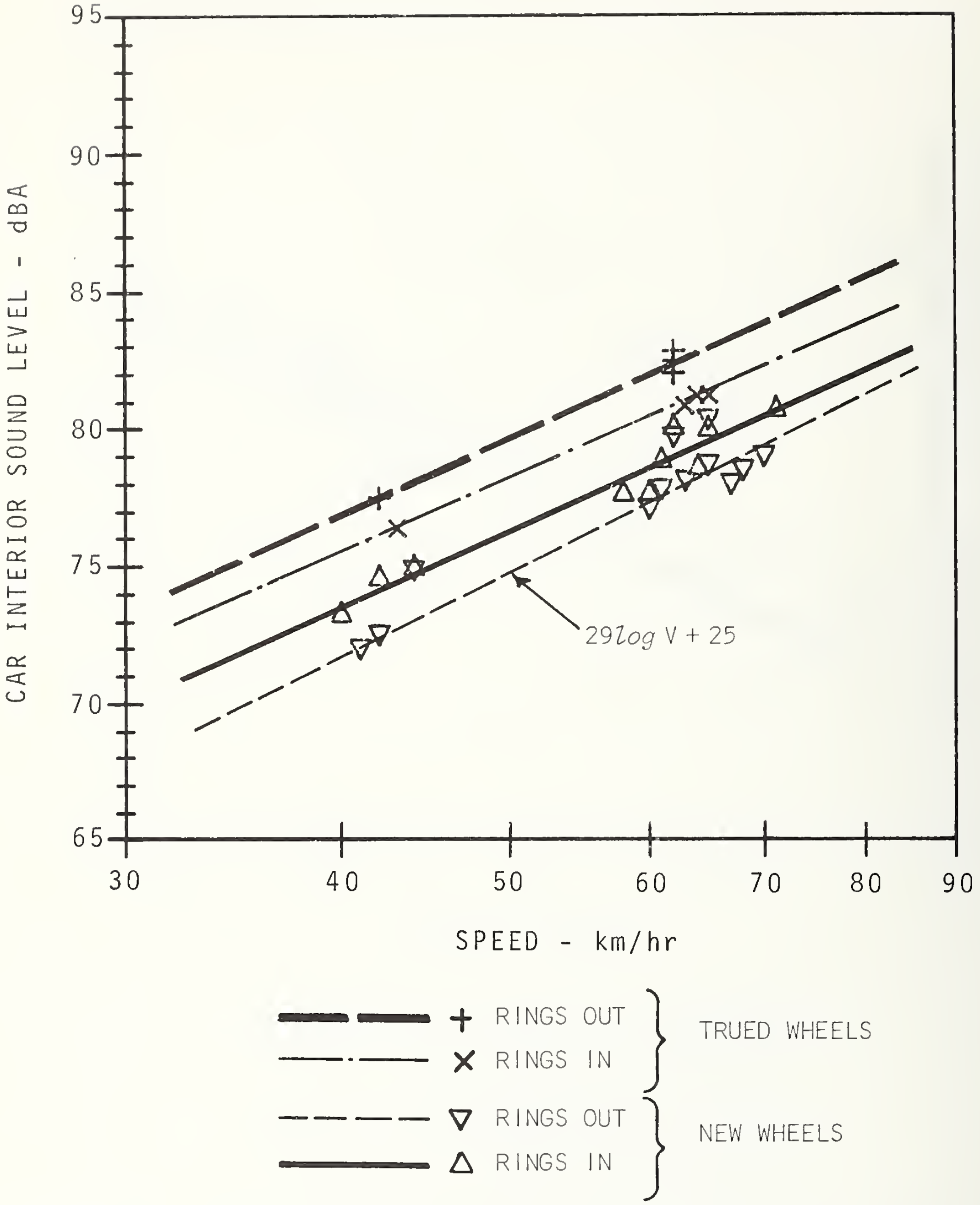


FIGURE 4-8. CAR INTERIOR SOUND LEVELS WITH AND WITHOUT RING DAMPERS, WORN TANGENT WELDED TRACK, NEW AND TRUED GROOVED WHEELS

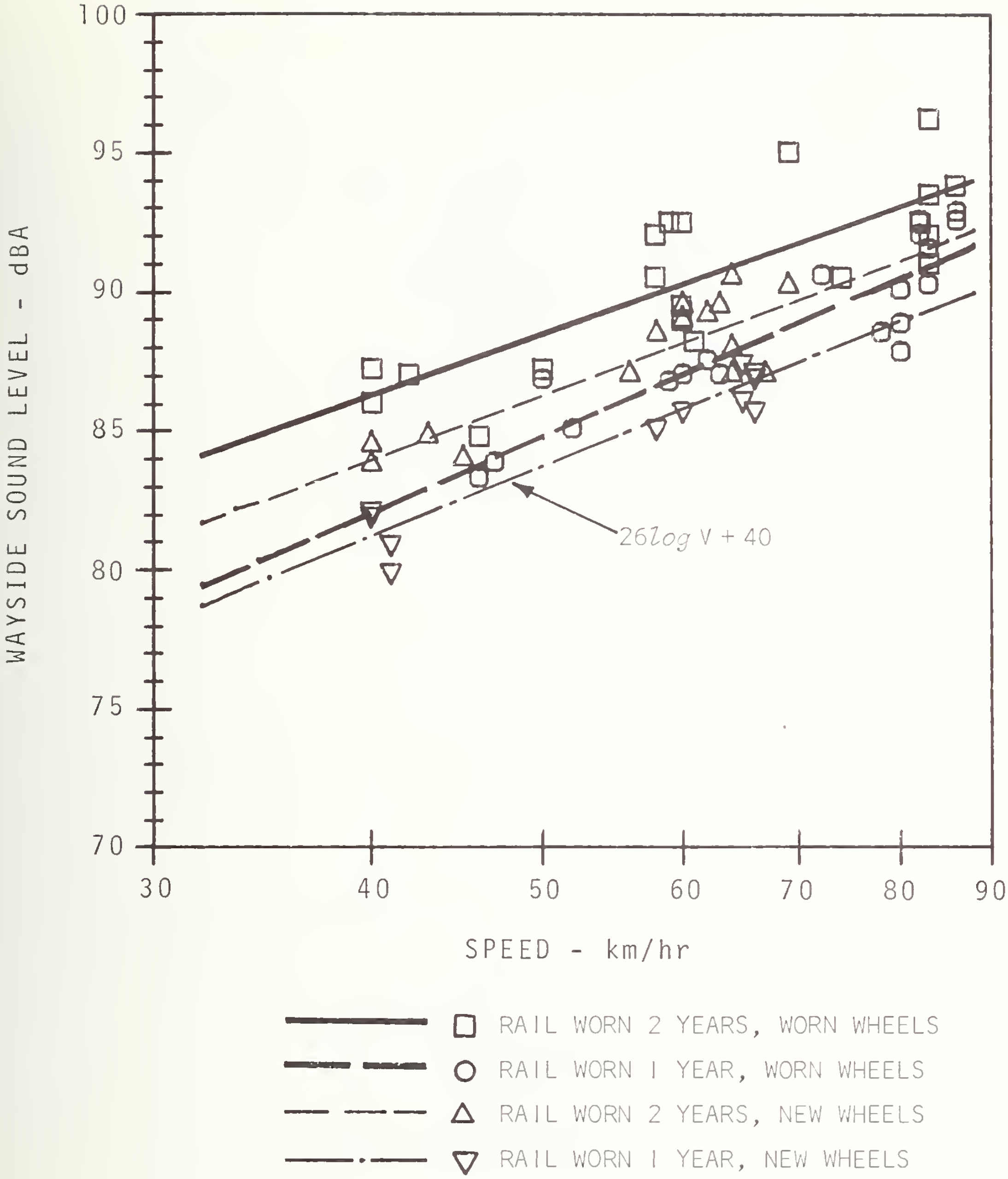


FIGURE 4-9. WAYSIDE SOUND LEVELS AT THE TANGENT JOINTED TEST TRACK WITH NEW AND WORN WHEELS AND WITH RAILS WORN 1 AND 2 YEARS

7.5 m FROM TRACK CENTERLINE

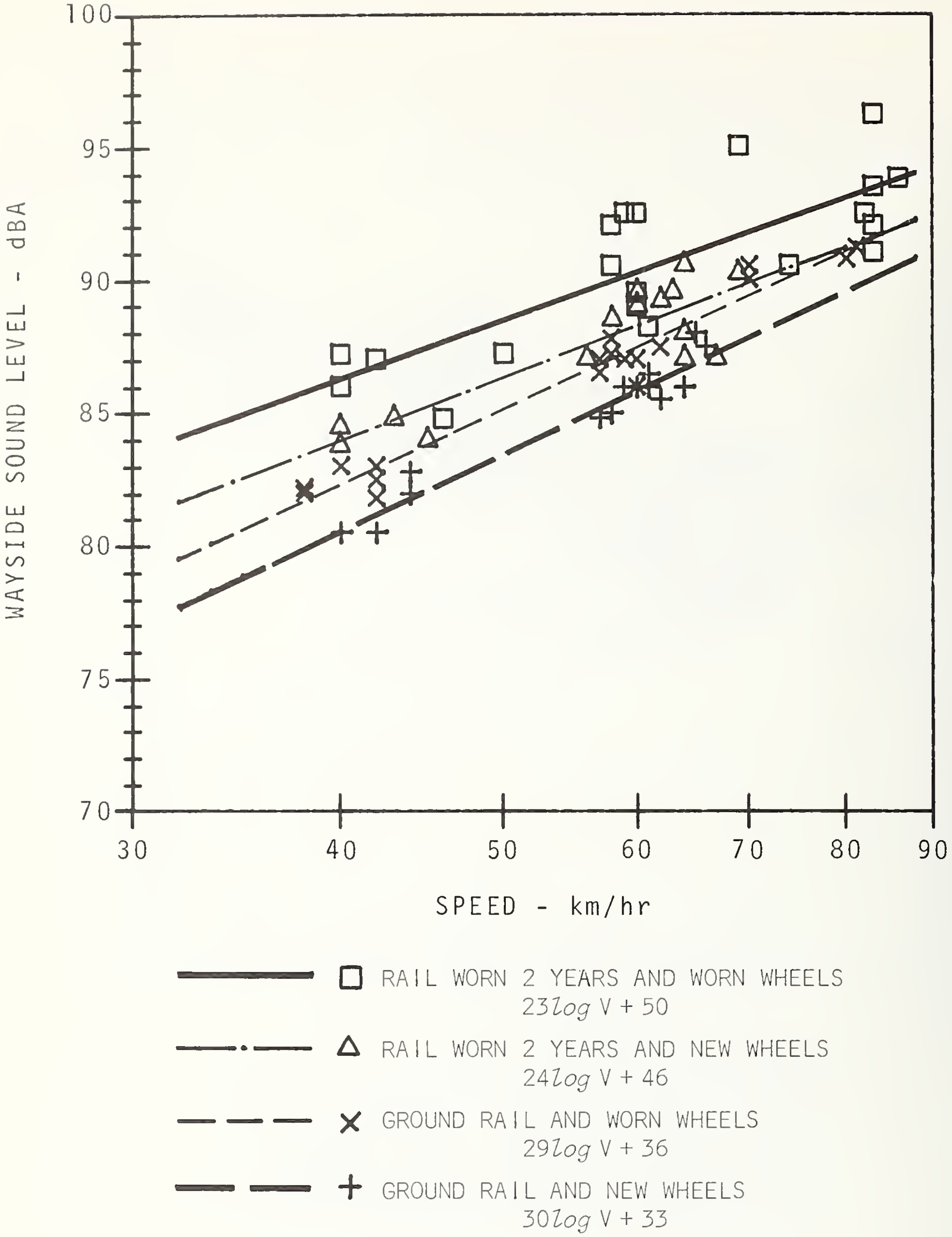


FIGURE 4-10. WAYSIDE SOUND LEVELS AT TANGENT JOINTED TEST TRACK WITH NEW AND WORN WHEELS AND WITH RAILS GROUND AND WORN TWO YEARS

7.5 m FROM TRACK CENTERLINE

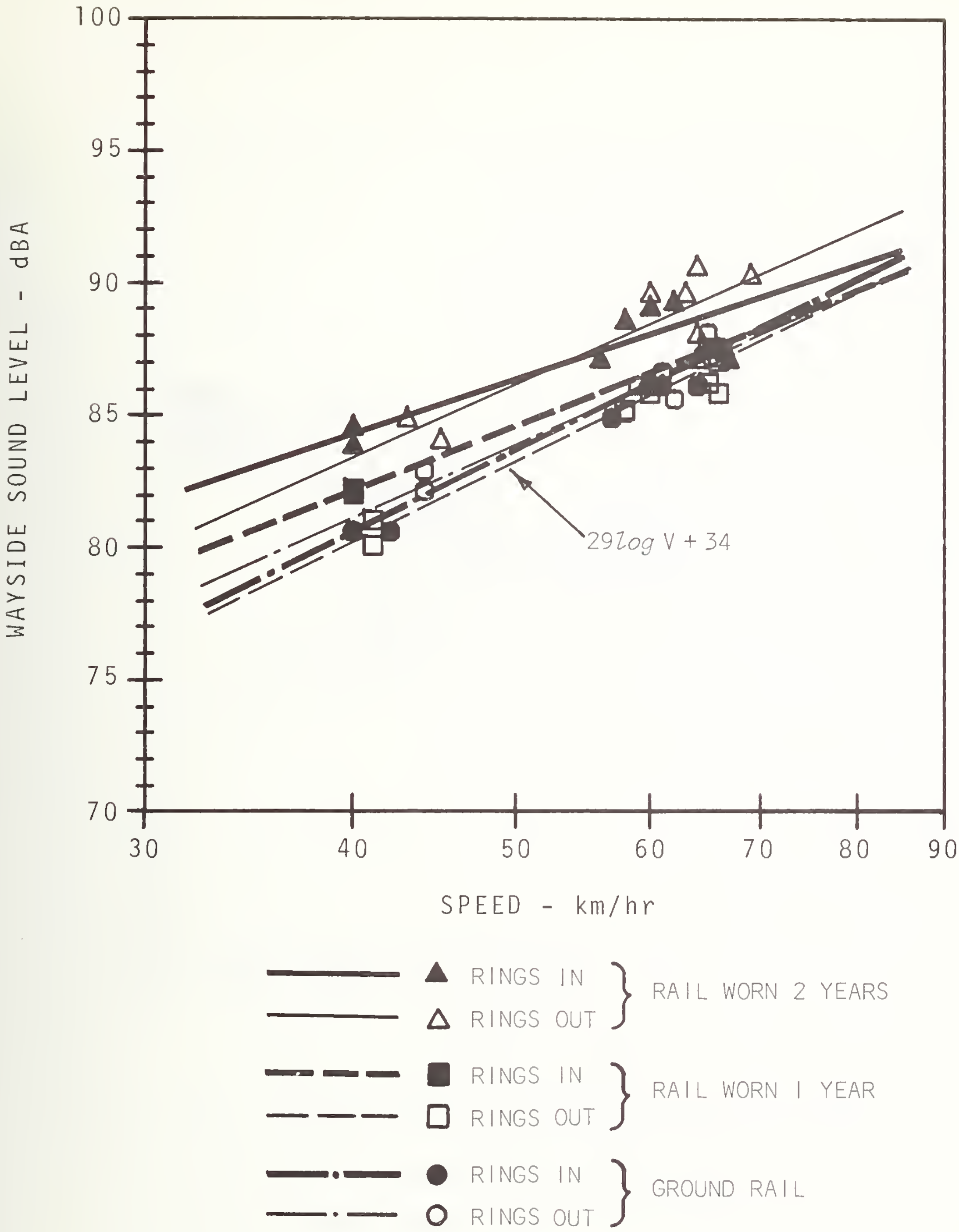


FIGURE 4-11. WAYSIDE SOUND LEVELS WITH NEW GROOVED WHEELS WITH AND WITHOUT RING DAMPERS, TANGENT JOINTED TEST TRACK

7.5 m FROM TRACK CENTERLINE

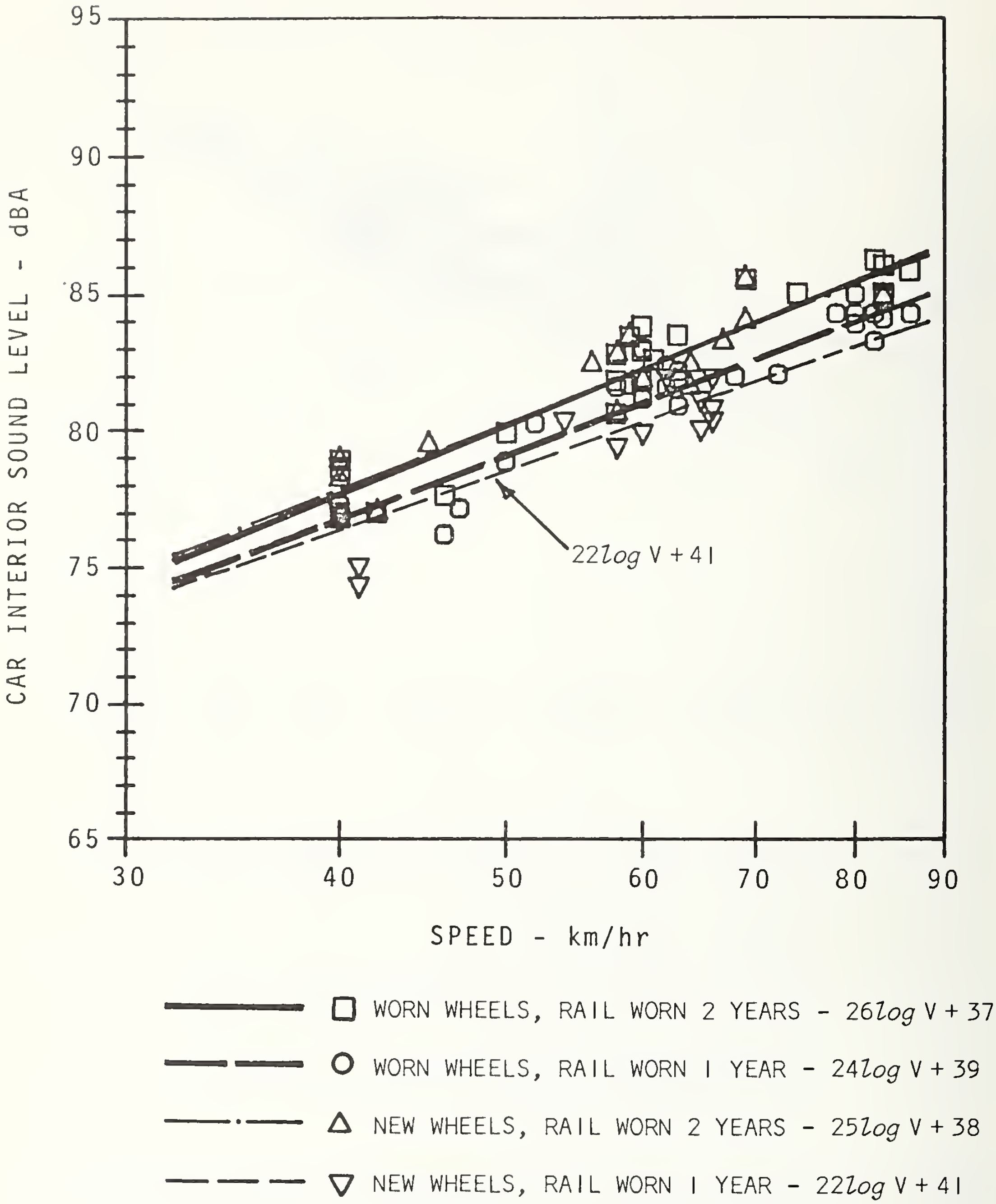


FIGURE 4-12. CAR INTERIOR SOUND LEVELS ON THE TANGENT JOINTED TEST TRACK WITH NEW AND WORN WHEELS AND WITH RAILS WORN 1 AND 2 YEARS - TEST SERIES 2

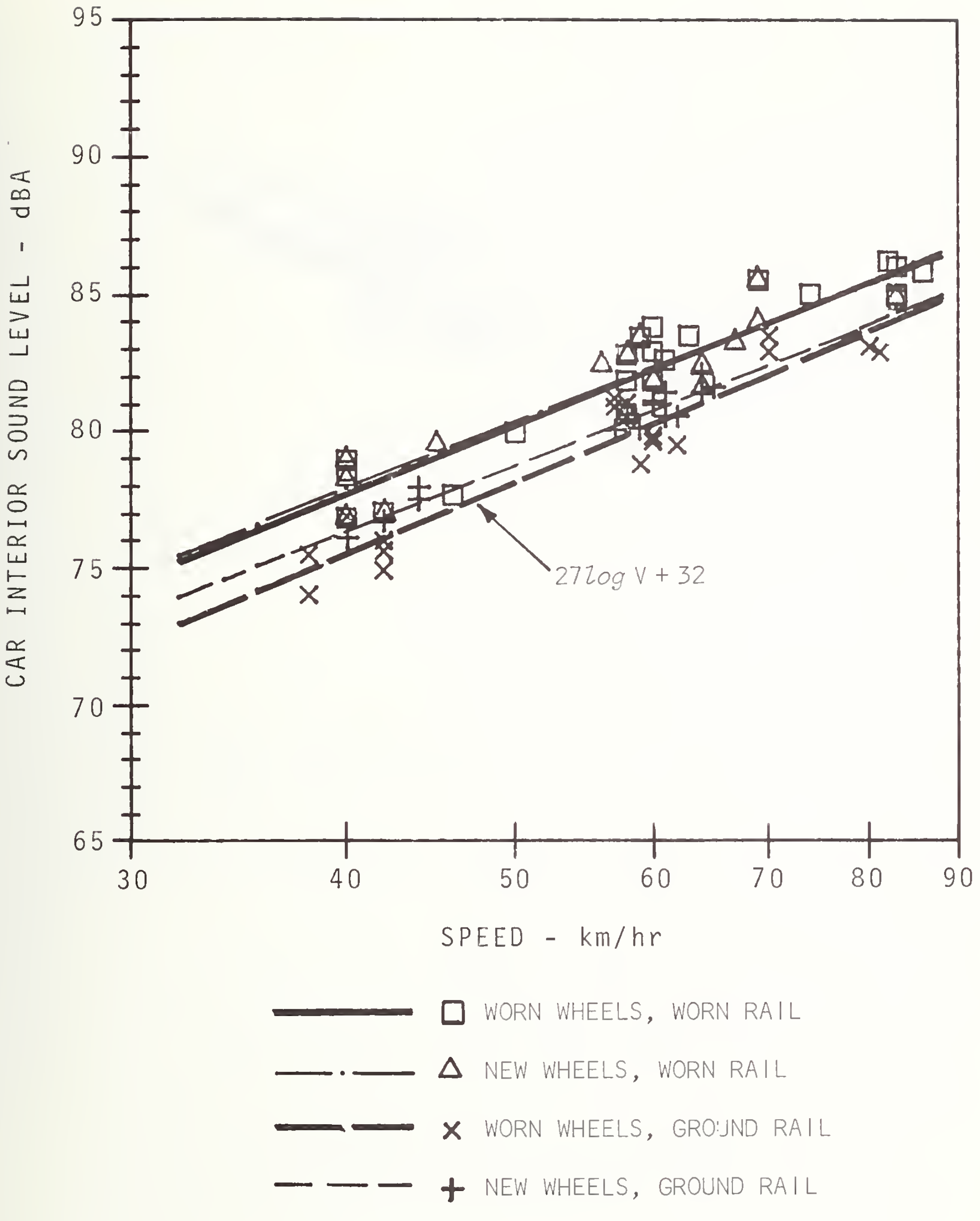


FIGURE 4-13. CAR INTERIOR SOUND LEVELS ON TANGENT JOINTED TEST TRACK WITH NEW AND WORN WHEELS AND WITH RAILS GROUND AND WORN 2 YEARS

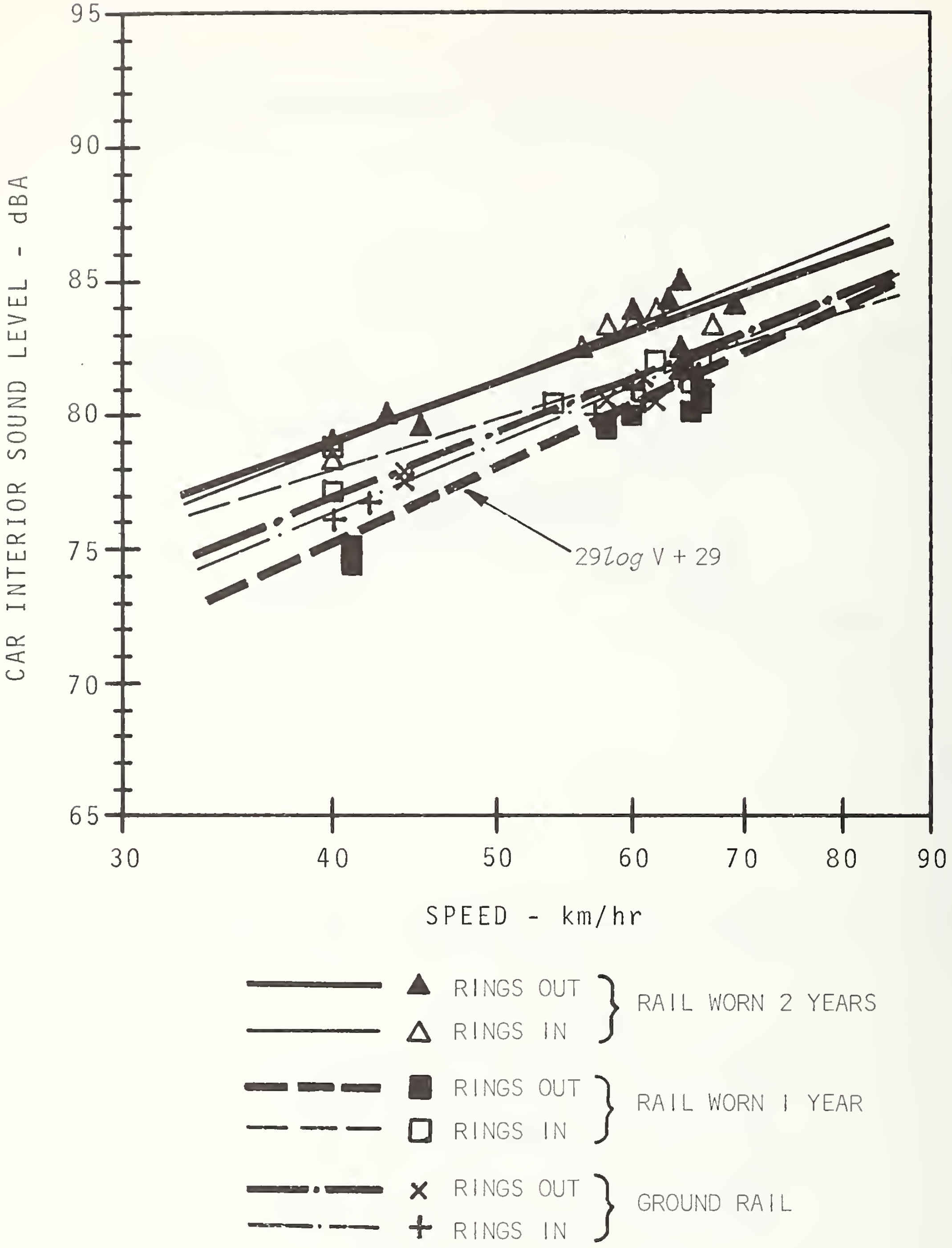


FIGURE 4-14. CAR INTERIOR SOUND LEVELS WITH NEW GROOVED WHEELS WITH AND WITHOUT RING DAMPERS, TANGENT JOINTED TEST TRACK

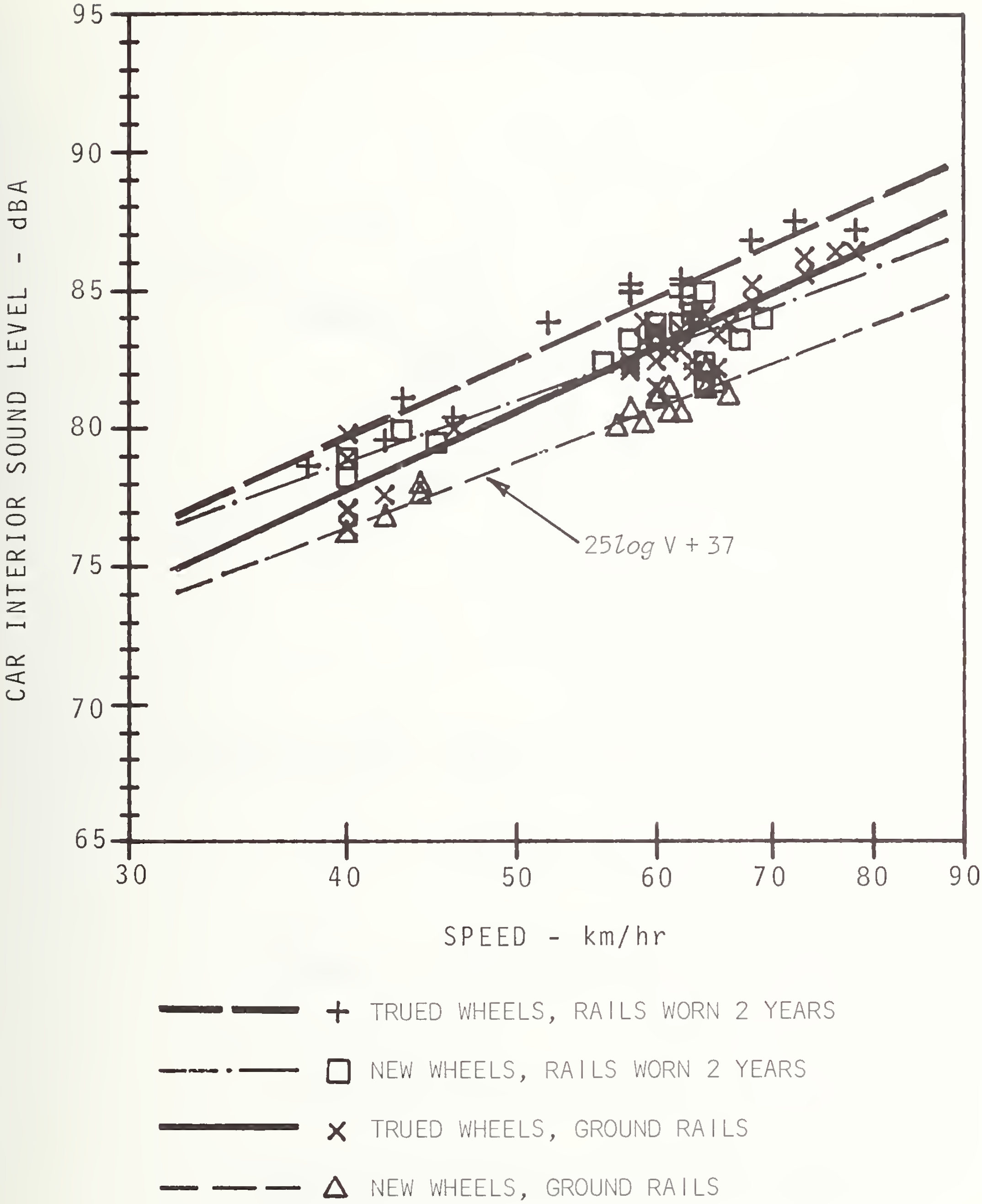


FIGURE 4-15. CAR INTERIOR SOUND LEVELS WITH NEW AND TRUED WHEELS ON THE TANGENT JOINTED TEST TRACK

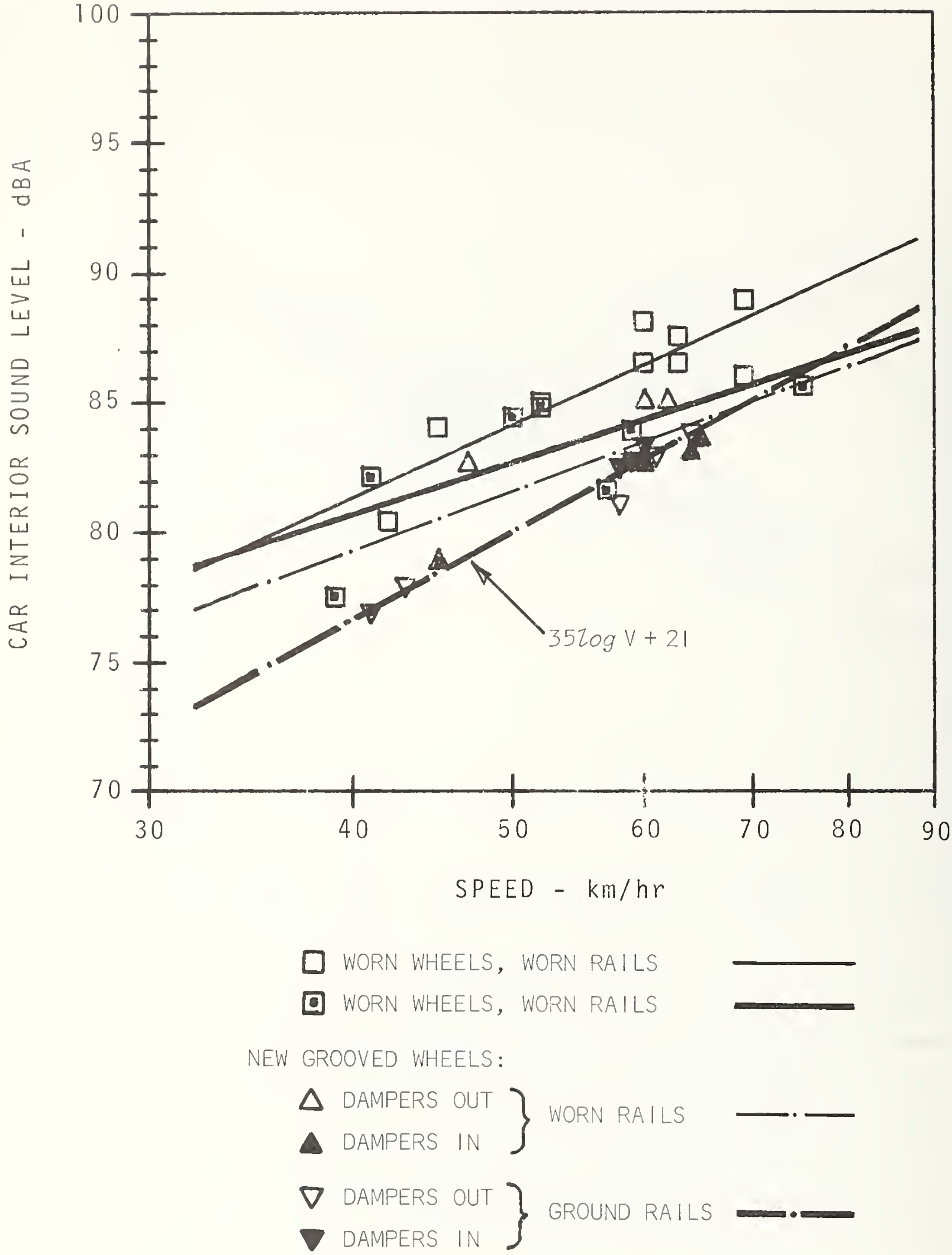


FIGURE 4-16. CAR INTERIOR SOUND LEVELS ON THE SUBWAY TEST TRACK, TANGENT WELDED RAILS

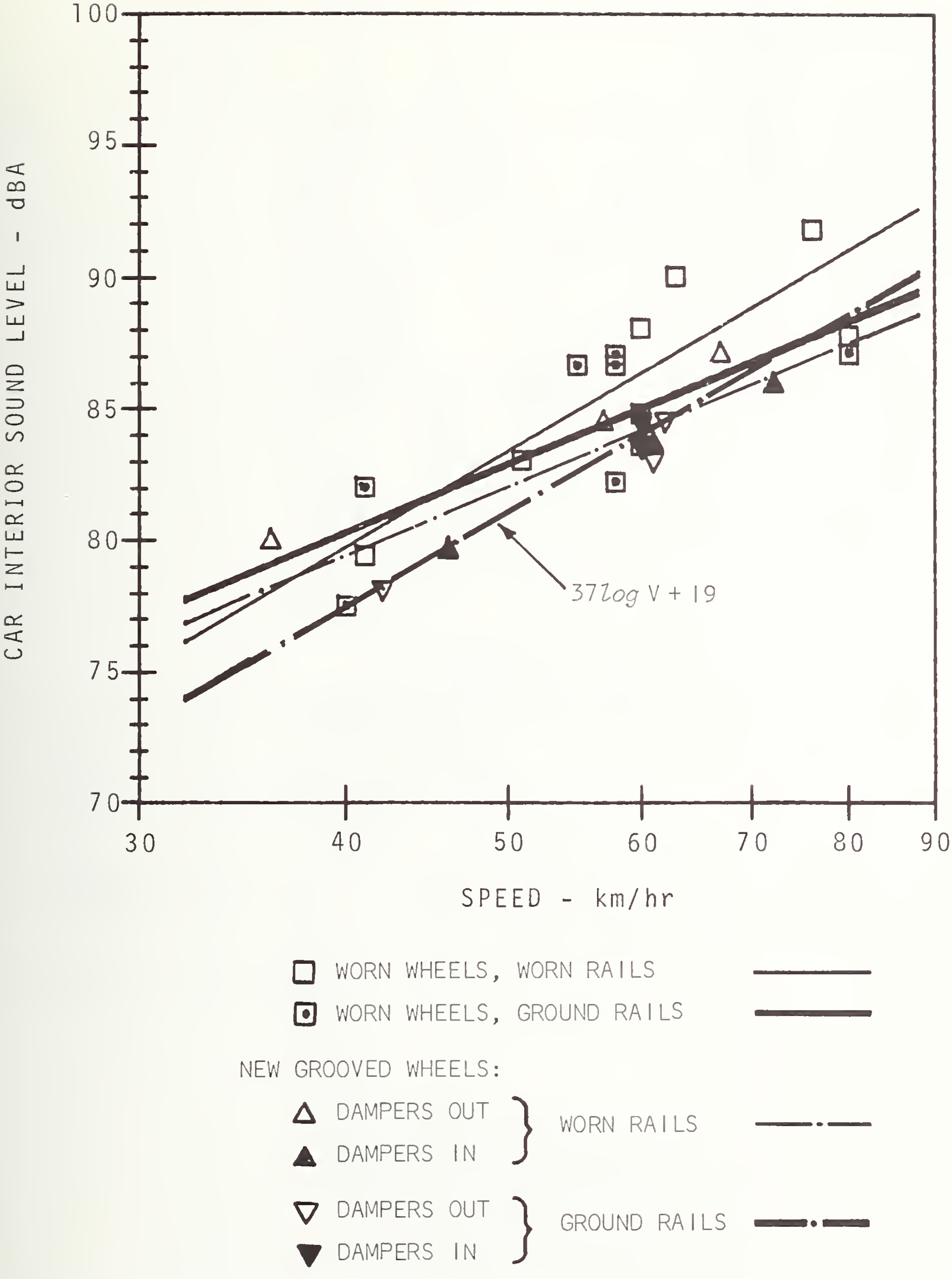


FIGURE 4-17. CAR INTERIOR SOUND LEVELS ON SUBWAY TEST TRACK, TANGENT JOINTED RAILS

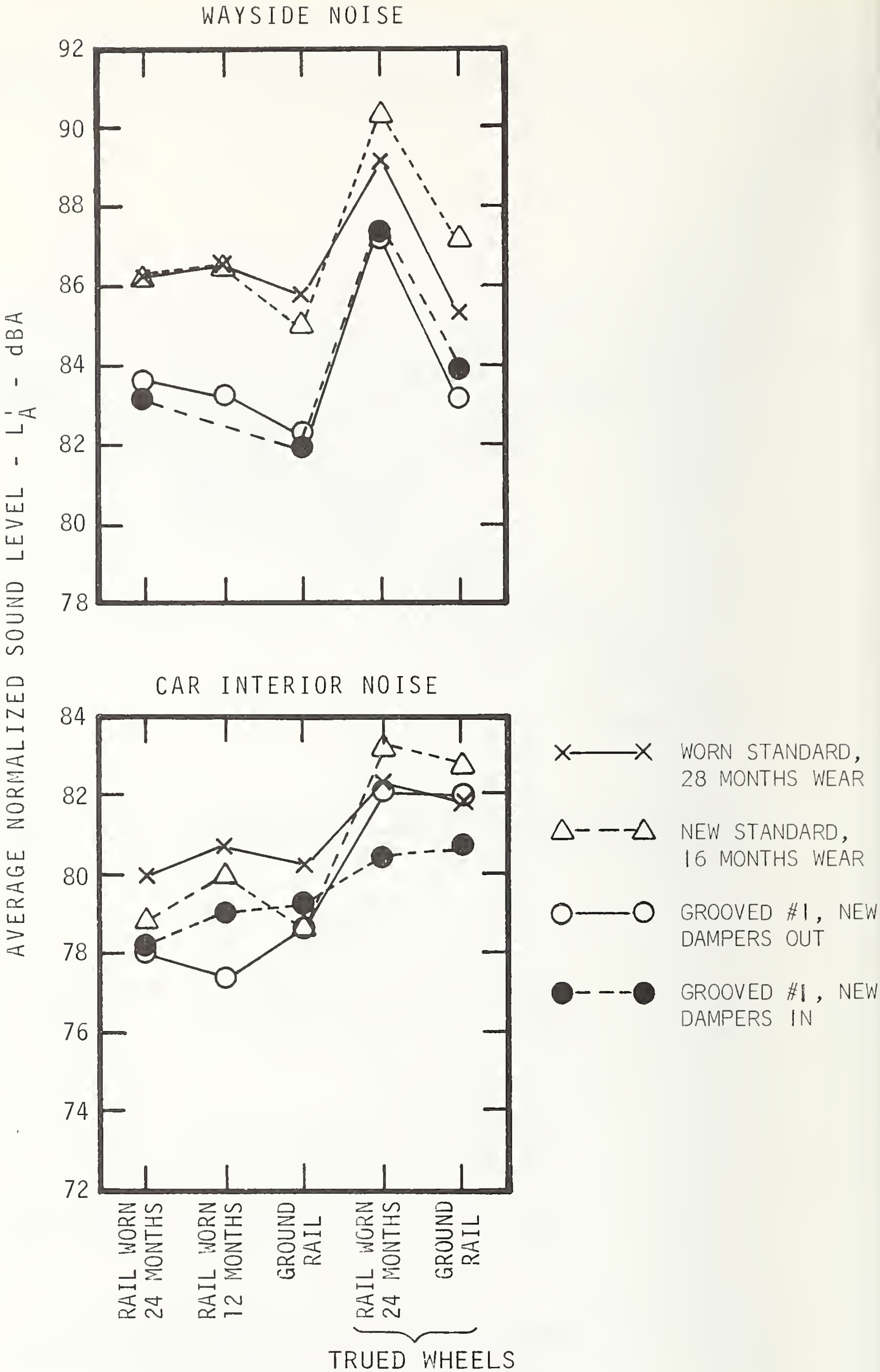


FIGURE 4-18. AVERAGE NOISE LEVELS AT TW TEST TRACK FOR VARIOUS WHEELS AND RAIL CONDITIONS

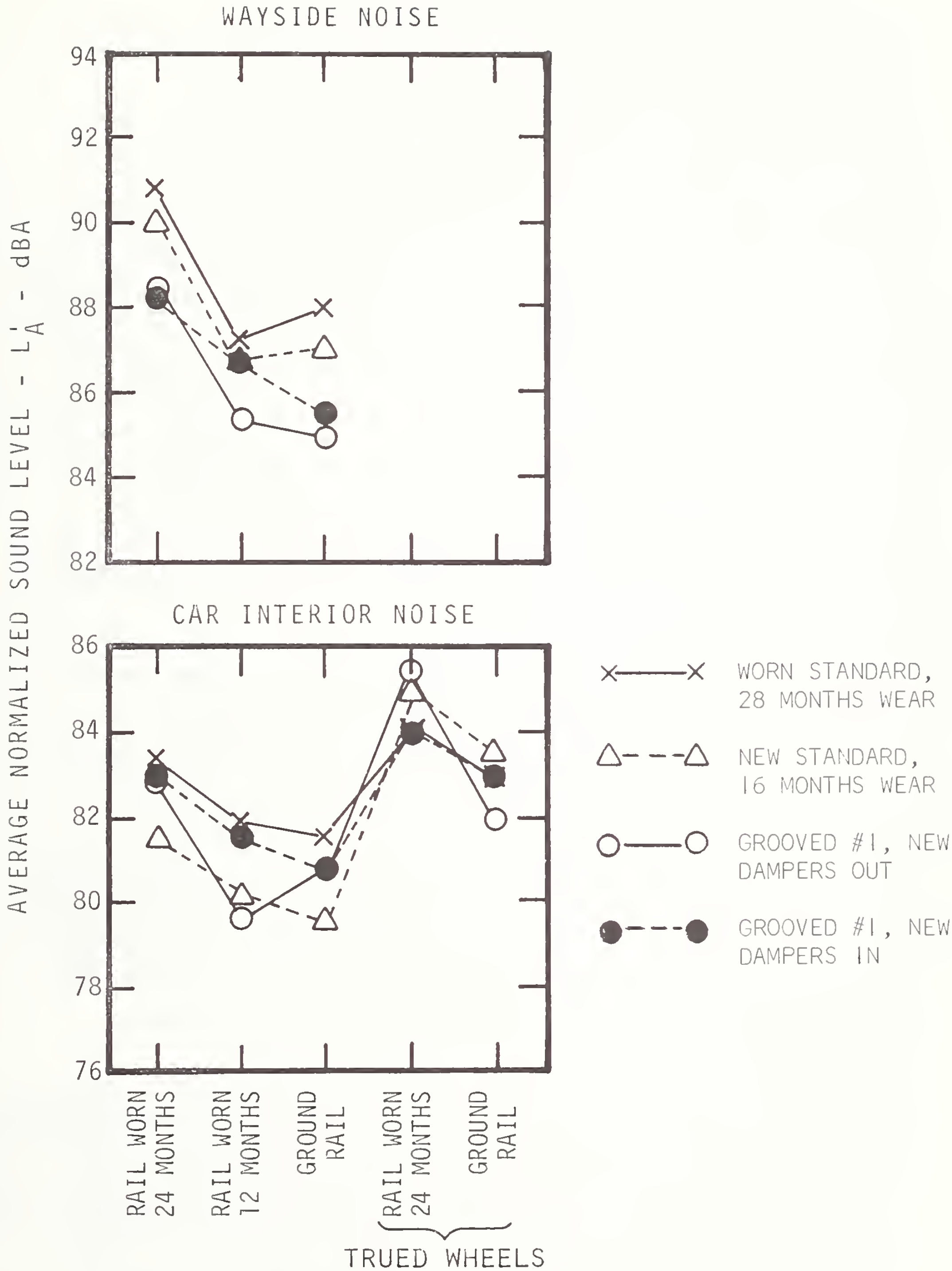


FIGURE 4-19. AVERAGE NOISE LEVELS AT TJ TEST TRACK FOR VARIOUS WHEELS AND RAIL CONDITIONS

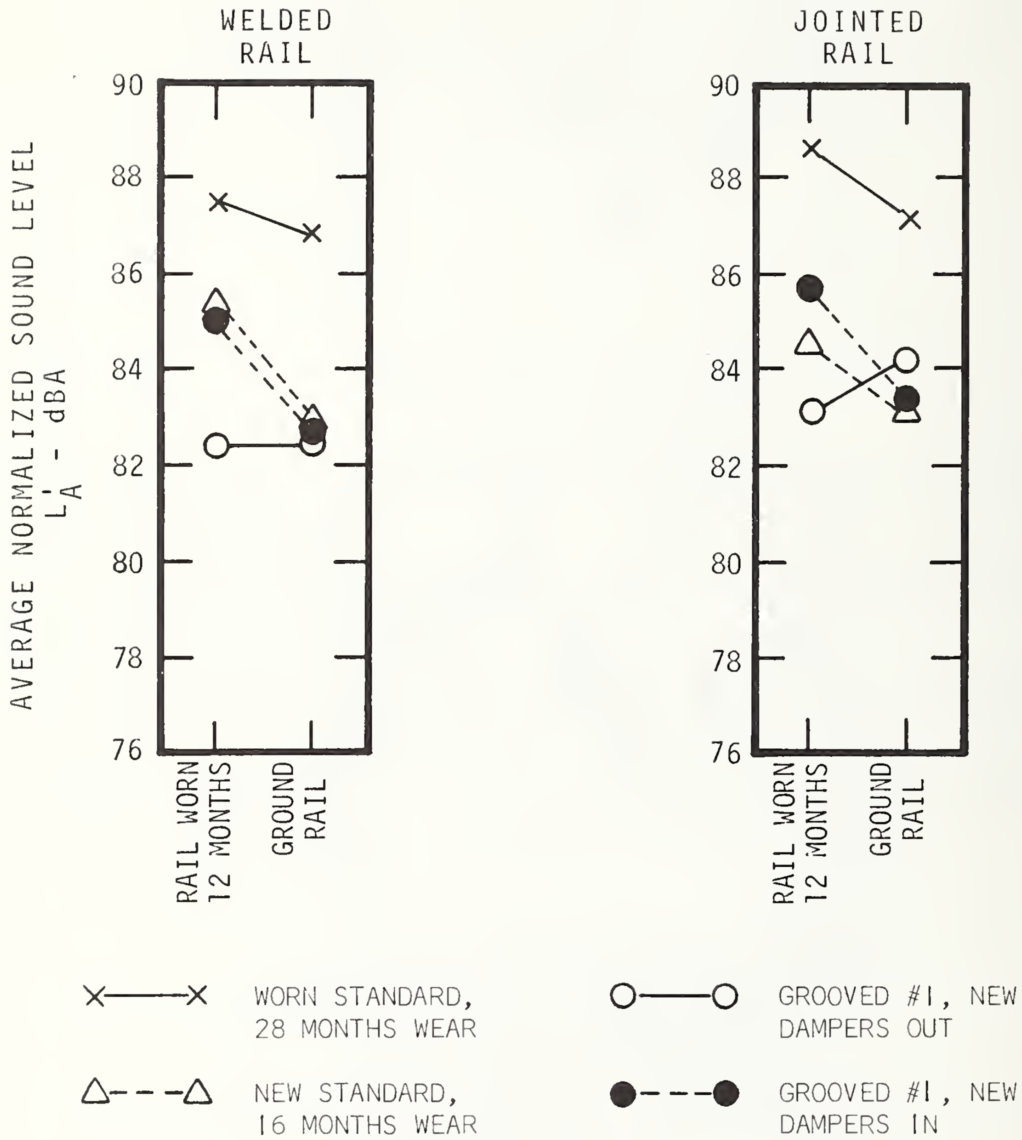


FIGURE 4-20 AVERAGE CAR INTERIOR NOISE LEVELS AT SUBWAY TEST TRACKS FOR VARIOUS WHEELS AND RAIL CONDITIONS

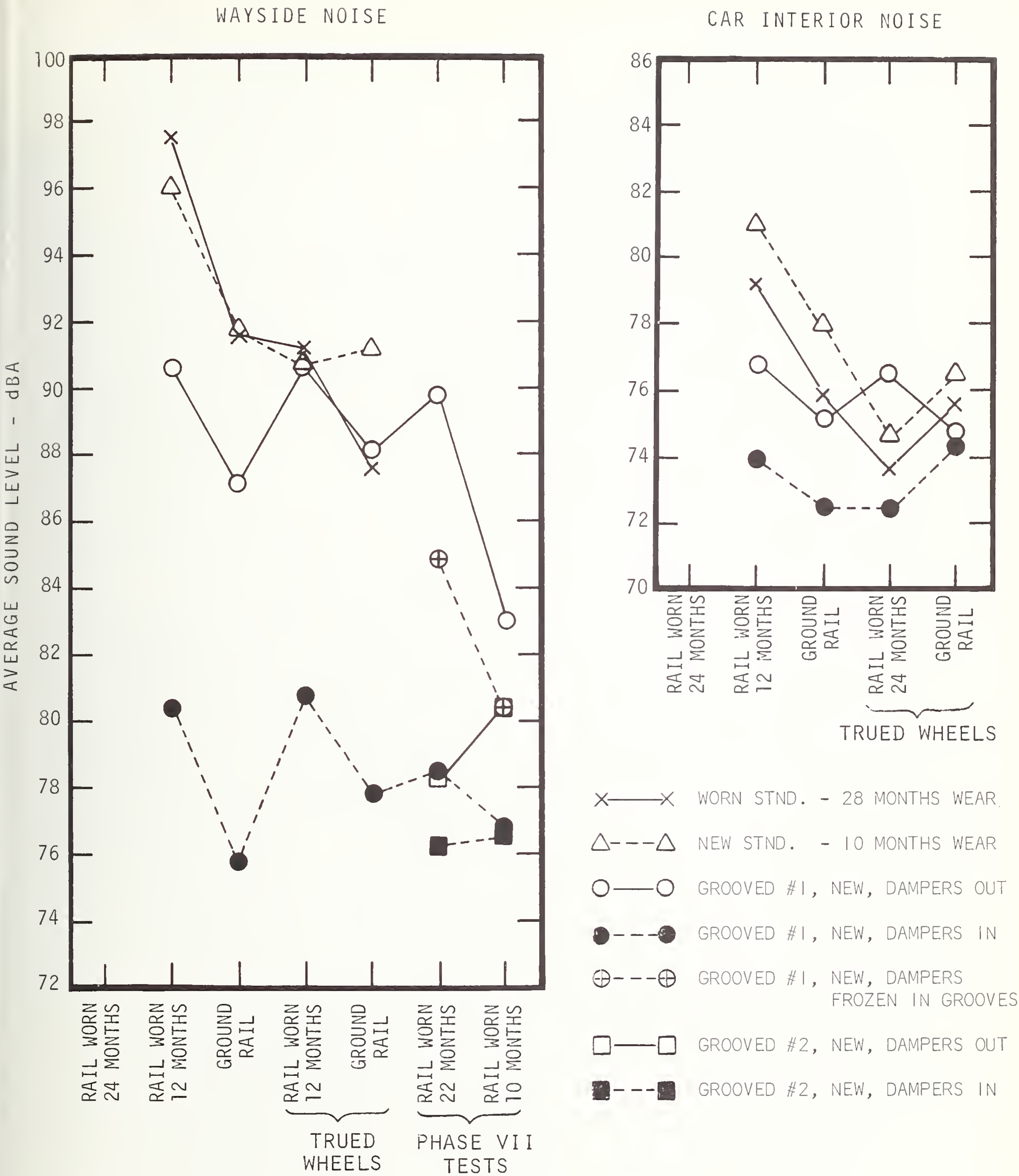


FIGURE 4-21. AVERAGE NOISE LEVELS AT TURN TEST TRACK FOR VARIOUS WHEELS AND RAIL CONDITIONS

4.2 RAIL GRINDING RESULTS

The Series 2 testing included measurements with worn and recently ground rails on the TW, TJ, TURN and SUB test tracks. This section presents the analysis of the noise reductions that were achieved with rail grinding.

At the time of the Phase IV tests, it had been approximately two years since the rails of the Control Segments of the TW and TJ test tracks had been ground. During this two year period the track was in normal revenue service. All the remaining segments of the test tracks had been ground at the time of either the Phase I or Phase II tests and were worn by approximately one year of revenue service at the time of the Phase IV tests.

The comparisons of the A-weighted noise levels for both wayside and car interior noise for train operation on the worn and the newly ground rails are presented in Tables 4-14 through 4-17. The results from the TW test track, Table 4-14 and Figure 4-5, indicate that rail grinding did not have any significant effect on the car interior noise. The only car interior difference large enough to be statistically significant is the 1.6 dBA increase in noise level with the Grooved #1 wheels. However, since the car interior differences with the other test trains, including the Grooved #1 wheels after wheel truing and with the ring-dampers installed, are not statistically significant, the indication is that the increase in car interior noise with the Grooved #1 wheels was due to factors other than the rail grinding.

The differences presented in Table 4-14 for rail worn 12 months compared to rail worn 24 months all indicate changes of sound level less than 1 dBA. Thus, the differences in the condition of the worn rails did not have any identifiable effects on the car interior or wayside noise for the tangent welded track.

The measurements with trued wheels were the only tests showing substantial differences between the noise level on the ground and worn segments of the TW test track. Before Phase VI all three sets of wheels were trued. The wayside noise level with the trued wheels averaged 3.6 dBA lower on the ground rail compared to the worn rail. This difference is both statistically and physically significant. This difference is not speed dependent as indicated by the best fit lines presented in Figures 4-3 and 4-4. A conclusion that can be drawn from these data is that rail grinding does produce some reduction of roar noise but with worn wheels the grinding of rails does not produce significant noise reduction.

Referring to Figures 4-2 and 4-17 it is apparent that in Phase VI (after truing the wheels) the wayside noise level increased at the TW track segment with worn rails and not at the track segment with ground rails. Also, the car interior levels increased slightly on both of the track segments, see Figure 4-6. As discussed in Section 4.3 the increase in noise level after truing the wheels is clearly a function of the manner in which the wheels were trued and is highly unlikely to be a result of changes in rail contour. The data collected are insufficient to determine the reason for the relatively large increase in wayside noise on the worn rails compared to the ground rails. The indication is that the milling cutter truing process increased the effective surface roughness of the wheels. This result tends to show that grinding continuously welded rail reduces noise more effectively for wheels with short wavelength roughness than for normally worn wheels which probably have a broader range of roughness wavelength.

The results of rail grinding on the TJ test track, presented in Table 4-15, show that both the wayside and car interior noise at the Control Segment were consistently higher than at the two Test Segments both before and after grinding the Test Segments. Further, comparing the noise levels before and after grinding the Test Segment rails indicates no significant change resulting from the rail grinding. Apparently, the initial grinding improved the noise generation conditions but 12 months wear did not produce any significant change.

The effect of rail grinding on the subway test tracks are presented in Table 4-16 and Figures 4-16 and 4-17. There are some contradictory results in these data, apparently due to the influence of factors other than rail grinding. The most noticeable contradictory data is for the grooved wheels with ring-dampers installed. In this case the noise level increased after grinding on the welded rail but decreased after grinding on the jointed rail. Further, the results with the grooved wheels without ring-dampers indicated an opposite trend. Without rings the before/after grinding levels are essentially equal on the welded rail and are 1 dBA higher after grinding on the jointed rail. These results are unlikely to be a result of installing ring-dampers and are most likely to have been caused by factors that could not be controlled in this study.

Table 4-17 presents the rail grinding results on the TURN test track. For the Phase V tests, the Test Segment of the TURN track was ground and the Control Segment left in a worn condition. Hence, the measurements of Phases V, VI and VII tests provide a direct comparison of worn and ground curved track.

As indicated in Table 4-17, the levels on the ground rails were consistenly lower than on the worn rails. The higher levels were due to more continuous squeal noise being generated, higher levels of squeal, and a larger number of the wheel normal modes being excited by the action of the wheels on the worn rails.

The difference between worn and ground rail is greatest for worn standard wheels. For most of the damped wheels and for the new and trued standard wheels the average differences are relatively small.

The rail grinding results are particularly interesting since the Test Series 1 measurements showed increases in levels of wheel squeal noise after rail grinding. The squeal levels for the ground rail in Phases I, II and III were consistently higher than for the worn rail. Unfortunately the tests in Test Series 1 had more uncontrolled variables than Test Series 2. When the Test Segment of the TURN track was ground during Phase I, inadvertently the Control Segment was also ground, defeating the "control" aspect of the Control Segment. Comparisons of the average wheel squeal levels in Table 4-10 from Test Series 1 and Test Series 2 indicate that the levels with ground rail are consistent between the two test series while the levels with worn rail are 4 to 5 dBA lower in Test Series 1 than in Test Series 2. It appears then that the noise levels on worn rail in Test Series 1 were unusually low due to uncontrollable factors such as residual grease on the rail.

The direct comparisons of worn and ground rail provide a basis for concluding that grinding curved rail does not provide consistent reduction of wheel squeal noise at short radius curves, regardless of wheel wear condition.

TABLE 4-14. EFFECTIVENESS OF RAIL GRINDING ON TW TEST TRACK - LEVELS RELATIVE TO RAIL WORN BY 24 MONTHS OF NORMAL REVENUE SERVICE - dBA

Train	Wheel Condition	Wayside		Car Interior	
		Rail Worn 12 Mo.	Rail Ground	Rail Worn 12 Mo.	Rail Ground
STANDARD WHEELS					
Grooved #1	New	-0.3	-1.4	-0.6	+1.6
New Stnd.	Worn, 16 Mo.	-0.2	-1.2	-0.1	-0.3
Worn Stnd.	Worn, 28 Mo.	+0.3	-0.4	+0.8	+0.3
Grooved #1	Trued	--	-4.1	--	-0.1
New Stnd.	Trued	--	-3.1	--	-0.3
Worn Stnd.	Trued	--	-3.8	--	-0.4
DAMPED WHEELS					
Grooved #1	New	--	-1.2	+0.8	+1.0
Grooved #1	Trued	--	-3.6	--	+0.3

TABLE 4-15. EFFECTIVENESS OF RAIL GRINDING ON TJ TEST TRACK - LEVELS RELATIVE TO RAIL WORN BY 24 MONTHS OF NORMAL REVENUE SERVICE - dBA

Train	Wheel Condition	Wayside		Car Interior	
		Rail Worn 12 Mo.	Rail Ground	Rail Worn 12 Mo.	Rail Ground
STANDARD WHEELS					
Grooved #1	New	-3.0	-3.4	-3.4	-2.2
New Stnd.	Worn, 16 Mo.	-3.2	-2.9	-1.3	-1.9
Worn Stnd.	Worn, 28 Mo.	-3.6	-2.8	-1.5	-1.9
Grooved #1	Trued	--	--	--	-3.6
New Stnd.	Trued	--	--	--	-1.4
Worn Stnd.	Trued	--	--	--	-1.0
DAMPED WHEELS					
Grooved #1	New	-1.5	-1.2	-1.4	-2.4
Grooved #1	Trued	--	--	--	-1.0

TABLE 4-16. EFFECTIVENESS OF RAIL GRINDING ON SUBWAY TEST TRACKS - CAR INTERIOR NOISE LEVELS WITH GROUND RAIL RELATIVE TO TRACK WORN BY 12 MONTHS OF REVENUE SERVICE - dBA

Train	Wheel Condition	Ground Welded Rail	Ground Jointed Rail
STANDARD WHEELS			
Grooved #1	New	+0.1	+1.0
New Stnd.	Worn, 12 Mo.	-2.4	-1.5
Worn Stnd.	Worn, 24 Mo.	-0.5	-1.4
DAMPED WHEELS			
Grooved #1	New	+2.3	-2.5

TABLE 4-17. EFFECTIVENESS OF RAIL GRINDING AT REDUCING WHEEL SQUEAL — LEVELS WITH GROUND RAIL RELATIVE TO LEVELS WITH RAIL WORN BY TWELVE MONTHS OF SERVICE

Train	Wheel Condition	Wayside	Car Interior
STANDARD WHEELS			
Grooved #1	New	-3.5	-1.7*
Grooved #2[1]	New	+2.1*	--
Grooved #1	Trued	-2.7	+0.7*
New Stnd.	Worn, 16 Mo.	-4.2	-2.9
Worn Stnd.	Worn, 28 Mo.	-5.9	-2.7
Grooved #1[1]	Worn, 10 Mo	-6.8	--
RING-DAMPED WHEELS			
Grooved #1	New	-4.6	-2.6
Grooved #2[1]	New	+0.5*	--
Grooved #1	Trued	-3.0*	+1.9
Grooved #1[1]	Worn, 10 Mo. [dampers frozen]	-4.5	--
Grooved #2[1]	Worn, 10 Mo. [dampers free]	-1.6*	--
AVERAGES			
STANDARD WHEELS, NEW & TRUED		-1.4	-0.5
WORN STANDARD WHEELS		-5.6	-2.8
DAMPED WHEELS[2]		-2.2	-0.3

*Differences are not statistically significant at 0.05 level.

[1] Phase VII tests, the Test Segment had 10 months of wear and the Control Segment 22 months of wear at the time of this test.

[2] Average excludes results with dampers frozen in grooves.

4.3 WHEEL TRUING RESULTS

The measurements of Test Series 2 included standard steel wheels in new condition, trued condition, worn 16 months, and worn 28 months. Comparisons of the noise levels with the various test trains indicate the influence of wheel condition on noise levels. The new wheels are characteristic of wheels that have been resurfaced with a lathe type truer while the trued wheels are wheels that were resurfaced with the SEPTA underfloor milling-machine-type truer.

In comparing the noise levels with the various trains it should be noted that for Test Series 2 the new standard wheel train, Cars 755/756, was part of a 3-car train in all of the tangent track tests. This was necessary because of an alteration of the test procedure requiring intermixing the test trains between revenue trains. SEPTA policy did not allow a married pair car set such as 755/756 on the system without another car to provide backup equipment. Car 607, one of the Grooved #1 wheels, was operated with Cars 755/756 with the ring-dampers installed. To minimize the effect of the extra car on the test train, the wayside noise levels were analyzed only during the period that Cars 755/756 were passing by. Hence, the presence of the extra car should not affect the data obtained.

The results of the comparisons for tangent track are presented in Tables 4-18 through 4-20. These tables in conjunction with Figures 4-1 through 4-17 indicate:

1. For both subway test tracks the car interior noise levels were 4 to 5 dBA lower with new wheels and 2 to 4 dBA lower with wheels worn 16 months compared to wheels worn 28 months.

2. Compared to wheels worn 28 months, the wheels worn 16 months produced slightly lower noise levels - 0 to 1.9 dBA lower.

3. An average of 2 to 3 dBA noise reduction was observed on the TW and TJ test tracks with wheels in new condition compared to 28 months wear.

4. For the tests at the TW and TJ test tracks after truing all three wheel sets, significant increases in noise level were observed for all tests except the wayside noise at the TW Test Segment.

The general conclusions that can be drawn are that wheel condition has a measurable effect on the wayside and car interior noise levels and that something in the wheel truing process results in significant increases in noise level when the wheels were freshly trued and had not been run in service to smooth out the milling cutter marks.

Prior to the Phase IV testing the wheels on all of the test trains were carefully inspected in the SEPTA shops. In this inspection all four wheels on the inside axles of Car 613, one of the worn standard wheel cars, were found to have spalled areas apparently resulting from wheel flats. These discontinuities in the wheel profiles certainly contributed to the higher noise levels observed with the worn standard wheels, however, the sound of individual impacts from the wheel flats was not discernable to the ear.

The effects of wheel truing on overall wheel squeal noise are presented in Table 4-21. As indicated, the wheel squeal levels with new and trued wheels were consistently lower than with the worn wheels. The wayside levels with new and trued wheels averaged approximately 6 dBA lower on the worn rail and approximately 4 dBA lower on the ground rail.

The conclusion indicated by the data of Table 4-21 is that wheel truing of the standard wheels can result in significant reductions of wayside squeal noise with the reduction on worn rail being greater than on ground rail. No statistically significant reduction was observed for truing the ring-damped wheels. Clearly this is because the ring-dampers eliminate most squeal noise, except when the rings are frozen in place, and there is very little squeal noise left for the wheel truing to affect.

The results summarized in Table 4-21 are generally consistent with the results with wheel truing in Test Series 1. The basic conclusion is that wheel squeal noise is partially mitigated by use of regular wheel truing.

TABLE 4-18. EFFECTIVENESS OF WHEEL TRUING IN REDUCING NOISE AT TW TEST TRACK - NOISE LEVELS RELATIVE TO STANDARD WHEELS WITH 28 MONTHS OF NORMAL REVENUE SERVICE - dBA

Train	Wheel Condition	Wayside			Car Interior		
		Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground	Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground
Grooved #1	New	-2.6	-3.2	-3.6	-1.9	-3.3	-0.6
New Stnd.	Worn, 16 Mo.	0	-0.1	-0.8	-1.0	-0.7	-1.6
Grooved #1	Trued	+1.1	--	-2.6	+2.1	--	+1.7
New Stnd.	Trued	+4.1	--	+1.4	+3.2	--	+2.6
Worn Stnd.	Trued	+3.0	--	-0.4	+2.8	--	+1.6

TABLE 4-19. EFFECTIVENESS OF WHEEL TRUING IN REDUCING NOISE AT TJ TEST TRACK - NOISE LEVELS RELATIVE TO STANDARD WHEELS WITH 28 MONTHS OF NORMAL REVENUE SERVICE - dBA

Train	Wheel Condition	Wayside			Car Interior		
		Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground	Rail Worn 24 Mo.	Rail Worn 12 Mo.	Rail Ground
Grooved #1	New	-2.4	-1.8	-3.0	-0.4	-2.3	-0.7
New Stnd.	Worn, 16 Mo.	-0.8	-0.4	-0.9	-1.9	-1.7	-1.9
Grooved #1	Trued	--	--	--	+2.1	--	+0.4
New Stnd.	Trued	--	--	--	+1.6	--	+2.1
Worn Stnd.	Trued	--	--	--	+0.6	--	+1.5

TABLE 4-20. EFFECTIVENESS OF WHEEL TRUING IN REDUCING NOISE AT THE SUBWAY TEST TRACKS - CAR INTERIOR NOISE LEVELS RELATIVE TO STANDARD WHEELS WITH 28 MONTHS OF NORMAL REVENUE SERVICE - dBA

Train	Wheel Condition	Welded Rail		Jointed Rail	
		Worn	Ground	Worn	Ground
Grooved #1	New	-5.0	-4.4	-5.5	-4.1
New Stnd.	Worn, 16 Mo.	-2.0	-3.9	-2.1	-4.2

TABLE 4-21. EFFECTIVENESS OF WHEEL TRUING AT REDUCING WHEEL SQUEAL - OVERALL NOISE LEVELS RELATIVE TO WORN STANDARD WHEELS - dBA

Train	Wheel Condition	Rail Worn 16 Mo.	Rail Ground	AVG.	Rail Worn 16 Mo.	Rail Ground	AVG.
STANDARD WHEELS							
Grooved #1[1]	New	-6.2	-4.6	-5.4	-3.0	-1.9*	-2.4
Grooved #2[2]	New	-11.5	-2.6*	-7.0	--	--	--
Grooved #1[1]	Trued	-6.0	-3.6	-4.8	-4.8	-1.3	-3.0
DAMPED WHEELS							
Grooved #2[2]	New	-2.2*	-0.1*	-1.2	--	--	--

*Differences are not statistically significant at the 0.05 level.

[1] The levels used for "worn standard wheels" are the average of standard wheels worn 12 months and 24 months.

[2] Comparisons from Phase VII tests, "worn wheels" had 10 months of wear.

4.4 RING-DAMPED WHEELS

The tests with ring-damped wheels were designed to measure the effectiveness of ring-dampers at controlling wheel/rail noise for a number of different combinations of wheel and rail conditions. During test Phases IV, V and VI measurements were performed with ring-damped wheels on Cars 607/644 on both worn and recently ground rail. The wheels were tested in the "new" condition with the running surface machined with a lathe type wheel truer, and after truing the wheels with the SEPTA underfloor wheel truer - a milling-machine-type wheel truer. In all cases measurements were made with the rings in and the rings out to provide a direct indication of the effectiveness of ring-dampers.

Because of the success of the ring-damped wheels at controlling wheel squeal as observed during the Phase IV, V and VI tests, the Phase VII tests were scheduled to further investigate ring-damped wheels on curved track. A set of wheels grooved on both the field side and the flange side was mounted on Car 606. In Phase VII, four tests were performed at the TURN test track with Car 606 - damping rings out, rings in both sides, rings in the field side only, and rings in the flange side only.

The original ring-damped wheels on Cars 607/644 were also tested in Phase VII. At the time of the Phase VII tests the wheels had been in normal revenue service for just over ten months. The original test plan included tests with Cars 607/644 with the damping rings in and the damping rings out. However, in the first Phase VII tests with Cars 607/644 with the damping rings in, a significant amount of squeal was observed. Subsequently the rings were found to be very rigidly frozen into the grooves and extremely difficult to remove from the grooves.

It was necessary to destroy several rings in order to remove them from the grooves. Because of the poor performance of the ring dampers with the rings frozen in place, an extra set of tests was performed with Cars 607/644 with new rings installed in the grooves. Hence, Cars 607/644 were tested with the rings frozen in place, without rings, and with new rings installed.

Due to a shortage of available cars at SEPTA, it was not possible to prepare a 2-car train with damper grooves on both sides of the wheels - only Car 606 could be prepared before the Phase VII testing. Hence, Car 606 was tested as a 1-car train. To provide a basis for comparison between wheel squeal with 1-car and 2-car trains, in Phase VII Car 607 was also tested as a 1-car train with and without ring-dampers. Car 606 created relatively low levels of squeal when tested without dampers; it is possible that the level would have been higher if a 2-car train was tested. However, the results from the tests with Car 607 as a 1-car train are not dramatically different from the results with Cars 607/644 as a 2-car train. The most significant difference is on the Control Segment without ring-dampers. In this case, the 1-car train averaged 6.9 dBA higher level than the 2-car train. The indication is that testing Car 606 in a 2-car train would not necessarily result in higher squeal levels with the ring-dampers out, and hence that tests with a 2-car train would not significantly change the test results.

Tables 4-22 and 4-23 present the average reductions achieved with ring-damped wheels on tangent track and curved track, respectively. The results on tangent track as a function of speed with and without ring-dampers are shown in Figures 4-3, 4-4, 4-7, 4-8, 4-11, 4-14, 4-16 and 4-17. The results indicate that there was no consistent noise reduction on tangent track resulting from the use of ring-dampers. On some test tracks the levels were as much as 2.7 dBA higher with rings in compared to rings out. The increase is most likely to have been caused by factors unrelated to the ring-dampers.

In contrast, the results on the curve test track, Table 4-23, show that ring-dampers significantly reduce wheel squeal. Dramatic reductions of A-weighted sound level were observed for the wayside noise. The reduction of the car interior noise levels was significant but of lower magnitude than at the wayside because of the sound insulating properties of the car body. The best indication of the effectiveness of the ring-damped wheels is obtained by inspection of the 1/3 octave band spectra.

Figures 4-22 through 4-25 present averaged 1/3 octave band charts for the various tests with wheels grooved for ring-dampers. Figure 4-22 provides a direct comparison of the wheel squeal spectra with damping rings in and out for Cars 607/644. The squeal noise generally consisted of components above 4000 Hz. With the rings installed the squeal noise was always reduced and in some cases eliminated.

Figure 4-14 shows the average spectra for the tests with Car 607. This chart shows that with all the configurations with damping rings in the squeal was virtually eliminated. There are some differences above 4000 Hz between the spectra with the dampers in. It is likely that these differences were caused by uncontrolled factors (e.g., temperature and humidity) and were not due to the changes in the damper configurations. As indicated by the data for Car 606 without ring-dampers, Car 606 did not generate as much wheel squeal even without damping rings. It is for this reason that, as shown in

Table 4-23, the average wayside reduction with ring-dampers was only 2.9 dBA for Car 606. However, the squeal frequency reductions were in the range of 13 to 26 dB.

One very significant observation of this study is that with sufficient corrosion the ring-dampers can lose their effectiveness. This was particularly evident in the Phase VII test results. Figure 4-24 shows the average spectra for Cars 607/644 from the Phase VII test results. High levels of squeal were generated when the rings were frozen in-place, only slightly less squeal than when the rings were removed. However, replacing the frozen rings with new rings virtually eliminated the squeal - a clear indication that the corrosion reduced the effectiveness.

Figure 4-25 presents the average spectra for all of the tests with Cars 607/644 with ring-dampers installed. The rings were solidly frozen in the grooves in the first tests of Phase VII and they had been in-place about one month before the Phase V tests. There was no problem removing the rings after the Phase V tests indicating that they were not rigidly corroded in-place. For the rest of the tests the rings had been installed just prior to the testing. The curves of Figure 4-15 strongly indicate that the more tightly the rings are constrained in the grooves the less damping they provide.

TABLE 4-22. REDUCTION OF SOUND LEVELS WITH RING-DAMPED WHEELS ON TANGENT TRACK - OVERALL SOUND LEVELS WITH DAMPERS IN RELATIVE TO DAMPERS OUT - dBA. ALL TESTS WERE WITH GROOVED #1 TRAINS.

Rail Condition	Wayside		Car Interior	
	New Wheels	Trued Wheels	New Wheels	Trued Wheels
TW				
Ground	-0.2	+0.6	-0.4	-1.2
Worn, 12 Mo.	--	--	+1.6	--
Worn, 24 Mo.	-0.4	+0.1	+0.2	-1.6
AVG.	-0.3	+0.3	-0.6	-1.4
TJ				
Ground	+0.6	--	0.0	+1.1
Worn, 12 Mo.	+1.4	--	+2.2	--
Worn, 24 Mo.	-0.1	--	+0.2	-1.5
AVG.	+0.6	--	+1.2	-0.2
SUB 1 [Welded]				
Ground	--	--	+0.3	--
Worn, 12 Mo.	--	--	+2.7	--
AVG.	--	--	+1.5	--
SUB 2 [Jointed]				
Ground	--	--	-0.9	--
Worn, 12 Mo.	--	--	+2.6	--
AVG.	--	--	+0.8	--

TABLE 4-23. AVERAGE EFFECTIVENESS OF RING-DAMPED WHEELS AT REDUCING WHEEL SQUEAL - OVERALL SOUND LEVELS WITH DAMPERS IN RELATIVE TO OVERALL SOUND LEVELS WITH DAMPERS OUT - dBA

Train	Wheel Condition	Wayside			Car Interior		
		Rail Worn	Rail Ground	AVG.	Rail Worn	Rail Ground	AVG.
Grooved #1	New	-10.2	-11.3	-10.8	-2.8	-2.5*	-2.6
Grooved #2	New	-2.1*	-4.6	-2.9	--	--	--
Grooved #1	Trued	-10.0	-10.3	-10.2	-2.4*	-1.2*	-1.8
Grooved #1	Worn[1]	-4.9	-2.6*	-3.8	--	--	--
Grooved #1	Worn[2]	-11.4	-6.2	-8.8	--	--	--
AVG.[3]	--	-10.5	-9.3	-9.9	-2.6	-1.8	-2.2

*Differences not statistically significant at 0.05 level.

[1] Phase VII Tests with Cars 607/644, rings frozen in place.

[2] Phase VII Tests with Cars 607/644, new rings installed.

[3] Average excludes tests with rings frozen in place and Grooved #2 tests.

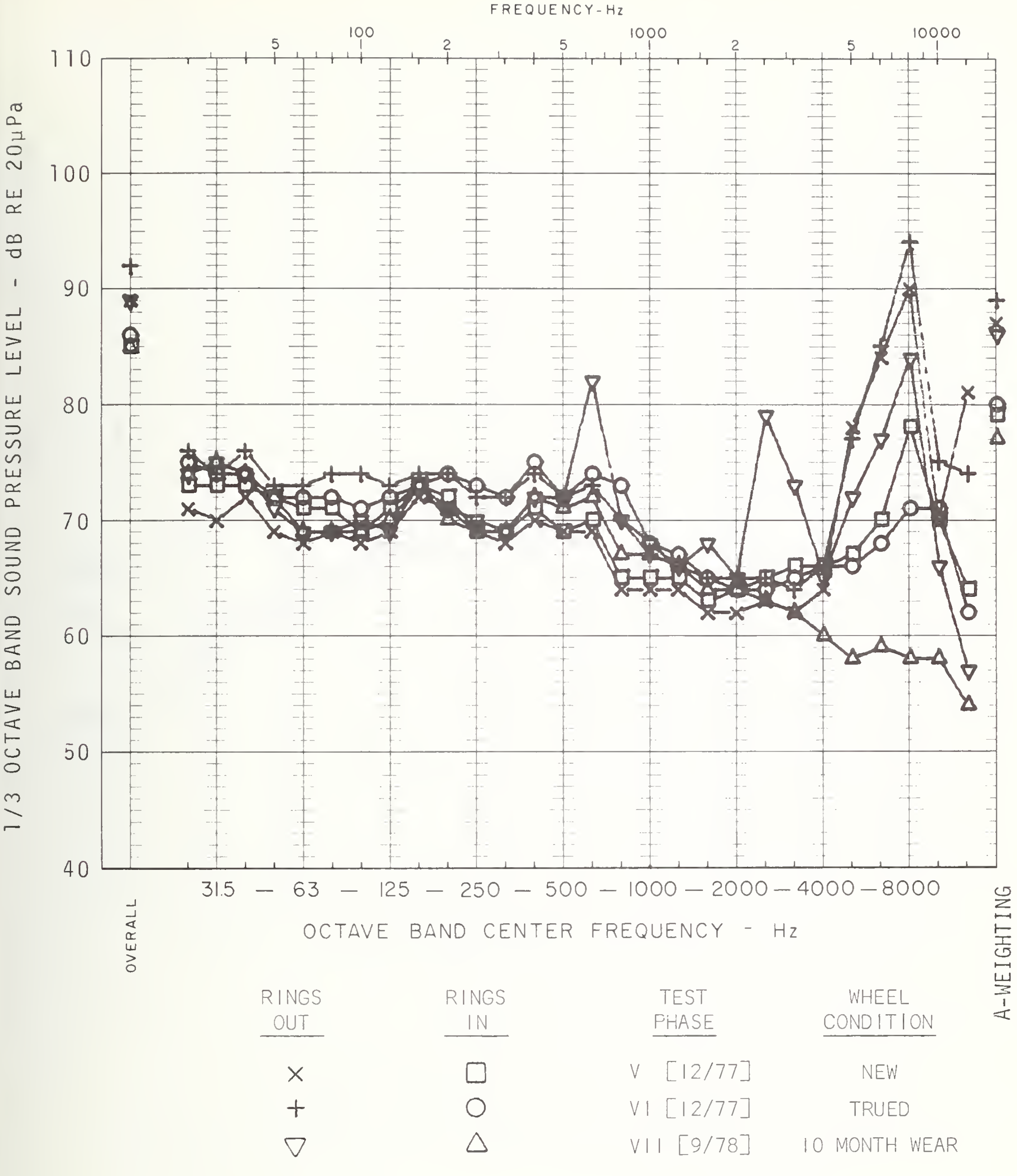


FIGURE 4-22. COMPARISON OF WHEEL SQUEAL WAYSIDE NOISE SPECTRA AT THE TURN TRACK FOR CARS 607/644 - AVERAGE OF SPECTRA ON GROUND AND WORN RAILS

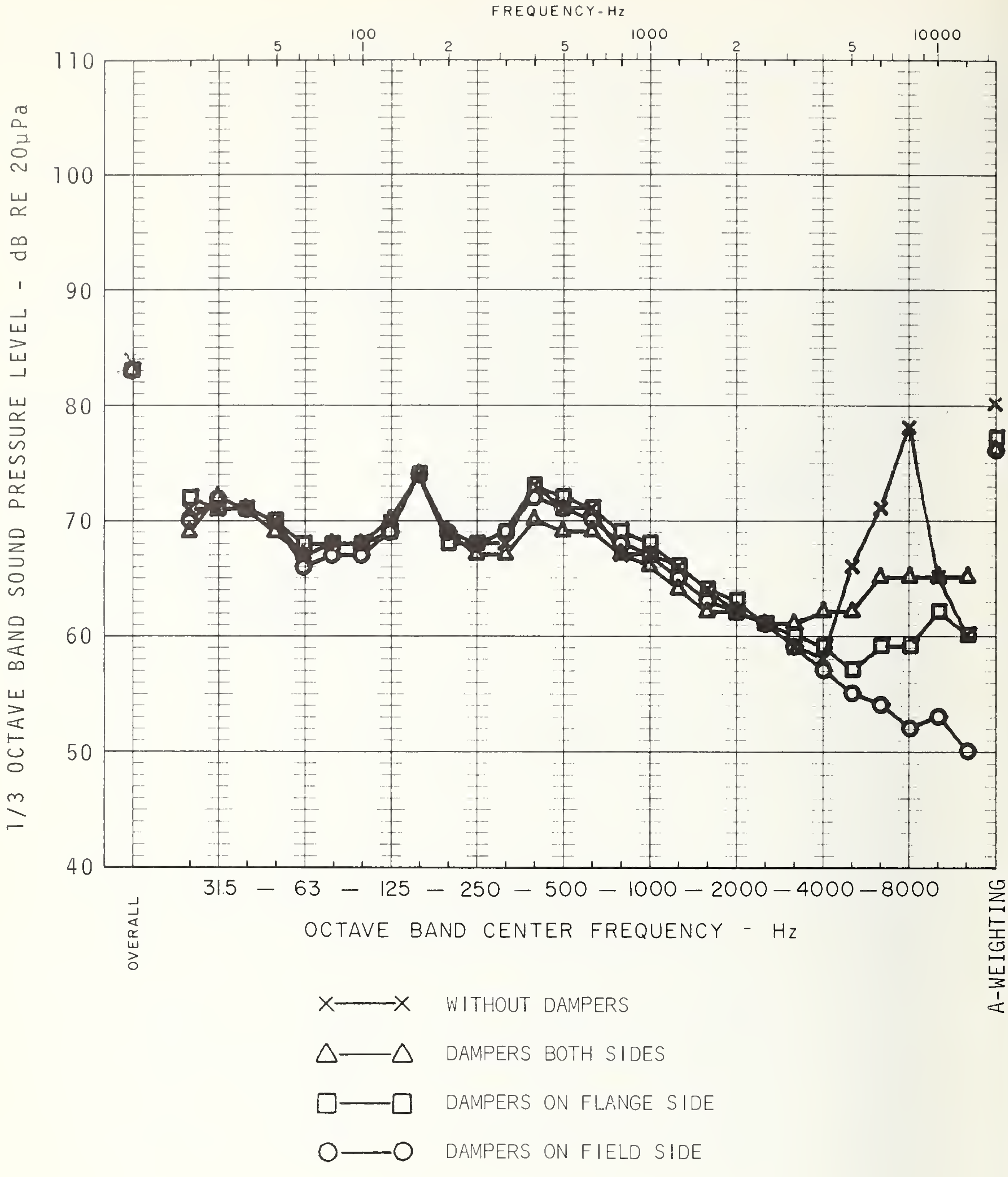


FIGURE 4-23. COMPARISON OF WHEEL SQUEAL WAYSIDE NOISE SPECTRA ON THE TURN TRACK FOR THREE RING-DAMPER CONFIGURATIONS

CAR 606, PHASE VII TESTS, 9-20-78

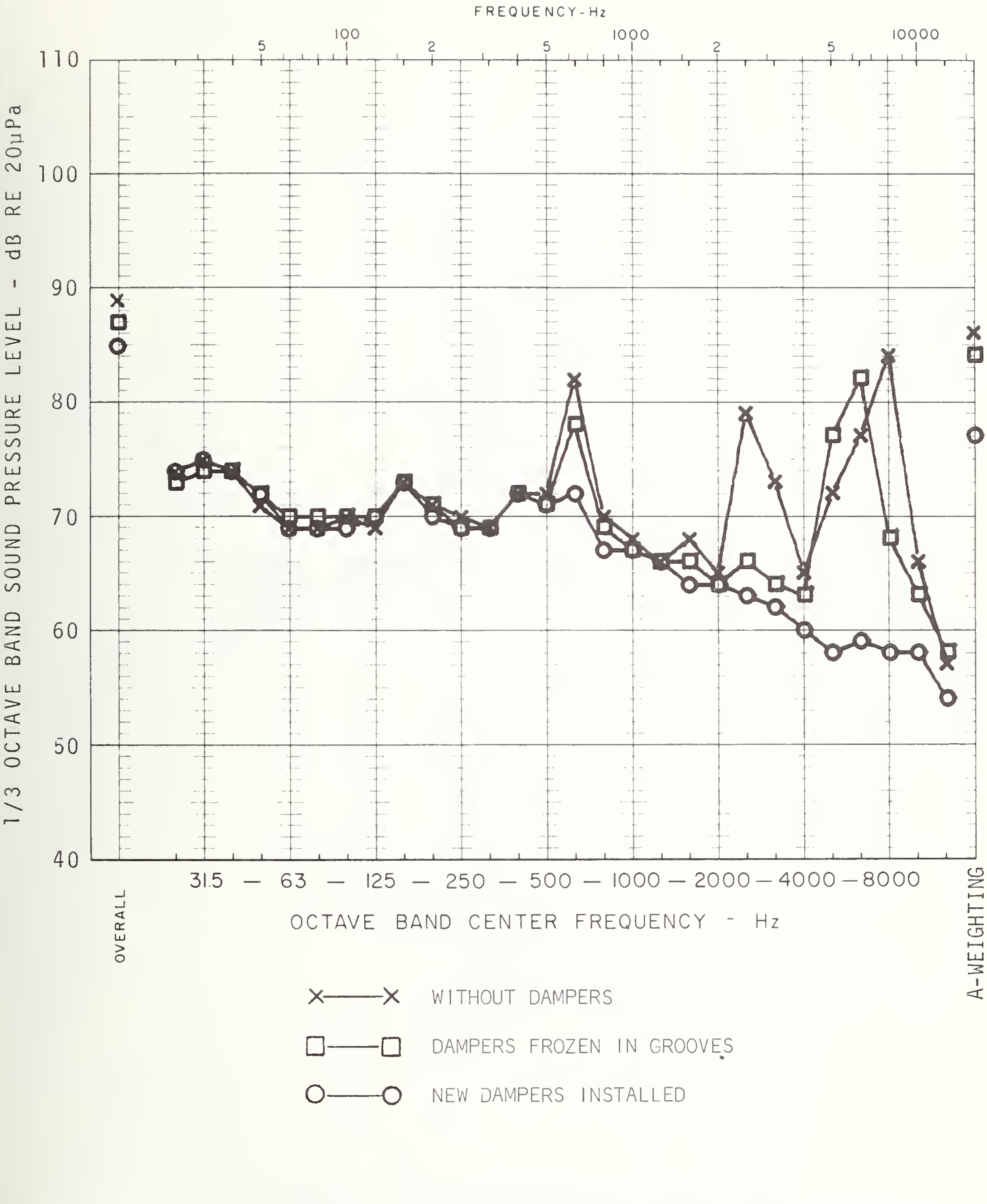


FIGURE 4-21. COMPARISON OF WHEEL SQUEAL WAYSIDE NOISE SPECTRA AT THE TURN TEST TRACK

CARS 607/644, PHASE VII TESTS, 9-20-78

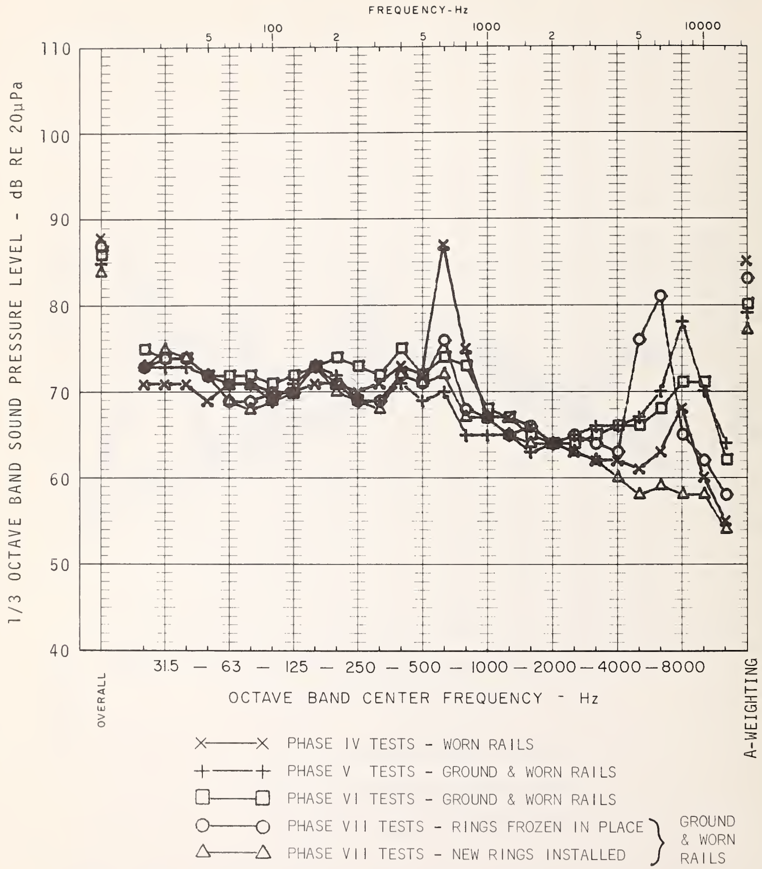


FIGURE 4-23 AVERAGE WHEEL SQUEAL WAYSIDE NOISE SPECTRA WITH RING-DAMPERS INSTALLED

CARS 607/644

4.5 EXTRA WAYSIDE TESTS

During the Phase IC measurements (September 2, 1976) an extra set of wayside noise tests were performed 15 m from the centerline of the Test Segment of the TW test track. These tests provide a direct comparison of the results at 7.5 m and 15 m from the track centerline and provide a basis for using the noise data at 7.5 m to estimate the noise levels at other distances within the adjacent community.

The locations of the two microphones relative to the elevated structure are shown in Figure 4-26. The microphone at 15 m was suspended above the street adjacent to the elevated structure on a rope stretched between the elevated structure and a sign bracket that extended approximately 6 m above the adjacent one-story building. Both of the microphones were approximately 1.5 m (4.9 ft) above the top-of-rail.

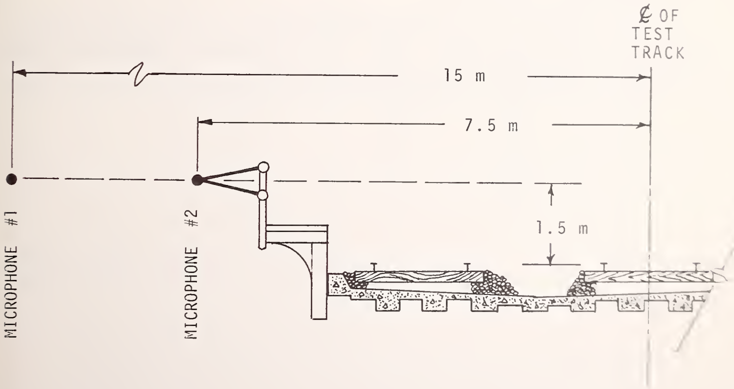


FIGURE 4-26. WAYSIDE MEASUREMENT LOCATIONS FOR EXTRA ELEVATED STRUCTURE TESTS

Table 4-24 presents the results of the extra wayside measurements. The difference between the levels at 7.5 m and 15 m are very consistent, averaging 6.5 dBA with the 1-car train and 5.7 dBA with the 2-car train. There are several models that can be used to estimate the attenuation of noise with increasing distance from the track.

Table 4-25 presents a summary of the differences between 7.5 m and 15 m as predicted by three models. The measured difference is greater than predicted by all three models, indicating that obstructions in the path from the microphones to the test track rails increased the sound attenuation. The extra attenuation could have resulted from diffraction and interference caused by the third rail, safety walk, railing, and other structural components of the elevated structure. The data indicates that the interference results in 1.2 to 2.5 dBA extra attenuation.

Even though the monopole line source is in closest agreement with the measurement data, the measurement results are too limited to indicate one model being more accurate than another.

TABLE 4-24. EXTRA WAYSIDE SOUND LEVEL MEASUREMENTS — TEST SEGMENT OF TW TRACK, PHASE IC, SEPTEMBER 1-2, 1976

Train	Speed	Wayside Sound Levels - dBA		
		7.5 m	15 m	Δ
Car 613	46	79.5	73	6.5
Car 623	48	80.2	74.5	5.7
	44	80.2	74.5	5.7
	60	86	79.2	6.8
	66	87	80.2	6.8
	59	85.2	78.2	7.0
	66	87.2	80	7.2
	80	90.5	84.2	6.5
Average				6.5
Cars 755/756	39	77	71.2	5.8
	58	83.2	77.8	5.4
	59	84.2	78.8	5.4
	70	87.5	81.8	5.7
	64	86	80.2	5.8
	81	--	84.2	--
	56	84.2	78	6.2
Average				5.7

TABLE 4-25. PREDICTED NOISE LEVEL DIFFERENCE DUE TO GEOMETRIC SPREADING BETWEEN 7.5 m AND 1.5 m FROM TRACK CENTERLINE

Noise Source Model	Attenuation - dB	
	1-Car Train	2-Car Train
Incoherent Line Source		
Monopole [Ref. 4 Appendix I]	5.3	4.5
Dipole [Ref. 5]	4.7	3.7
Discrete Monopole Sources [Ref. 4, Appendix I]	4.0	3.2
Measured Difference	6.5	5.7

5. GROUND-BORNE VIBRATION TEST RESULTS

During several of the Phase II acoustical tests, structure-borne and ground-borne vibration measurements were performed at the same time by personnel of the Port Authority of New York and New Jersey. This section presents the test procedures, test locations, and the results of the vibration measurements.

The vibration created by rail transit operations has often resulted in noise and/or vibration intrusion inside neighboring structures. The vibration generated at the wheel/rail interface is transmitted from the rail through the transit structure and the intervening soil to adjacent buildings. The resulting building vibration may be perceptible as mechanical vibration of the building and/or as noise. The noise is radiated from the structure-borne vibration of building surfaces and when audible it is perceived as a low frequency rumble.

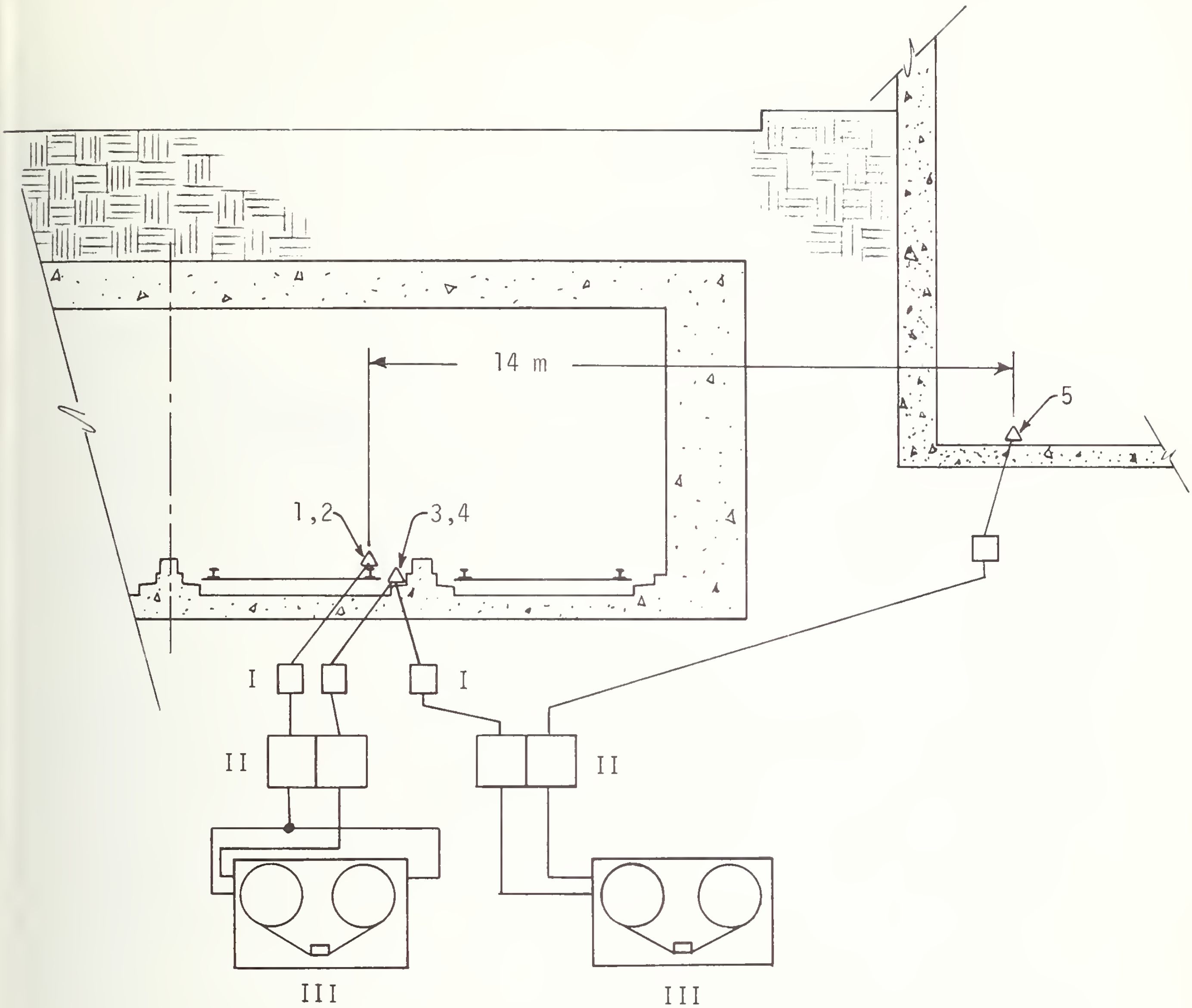
In areas where ground-borne vibration and noise may result in intrusion, special design features can be incorporated into the transit structures and rolling stock to reduce the levels of vibration. However, on existing facilities there are relatively few practical methods for reducing vibration. The results reported here provide information on the effectiveness of rail grinding, wheel truing and resilient wheels at reducing the levels of vibration as measured at the SEPTA facilities.

5.1 TEST PROCEDURES AND LOCATIONS

The vibration tests were performed on welded sections of tangent track in the subway and on the ballast and tie elevated structure. The equipment utilized to collect the vibration data and the accelerometer locations are shown schematically in Figures 5-1 and 5-2. In the subway five channels of vibration data were recorded using four accelerometers. The first accelerometer was located on the web of the rail to measure vertical vibration of the rail. The accelerometer was attached to the rail with a magnet and an insulated stud. The insulated stud was used to aid in reducing electrical interference. As indicated in Figure 5-1, the signal from this accelerometer was recorded in the direct and the frequency modulated modes to provide rail vibration data over an extended frequency range. A small metal block (an approximately 3 cm cube) was epoxied to the subway invert for mounting the second and third accelerometers in the vertical and lateral directions, respectively. The fourth accelerometer was attached directly to the basement floor of a building adjacent to the subway structure.

On the elevated structure two accelerometers were used, the first on the rail to give rail vertical acceleration and the second on the concrete deck of the elevated structure to provide data on structure vibration in the vertical direction. As in the subway, the signal from the accelerometer mounted on the rail was recorded in both the direct and FM modes to provide an extended frequency response range.

The measurement system consisted basically of piezoelectric accelerometers (self-generating units), accelerometer preamplifiers to drive long cables, signal conditioning amplifiers and magnetic tape recorders. The tape recorders used were 3-channel machines which, in combination with the signal conditioning amplifiers, are arranged to permit recording either in the FM mode on all three channels or in the direct analog mode on one or two of the three channels.

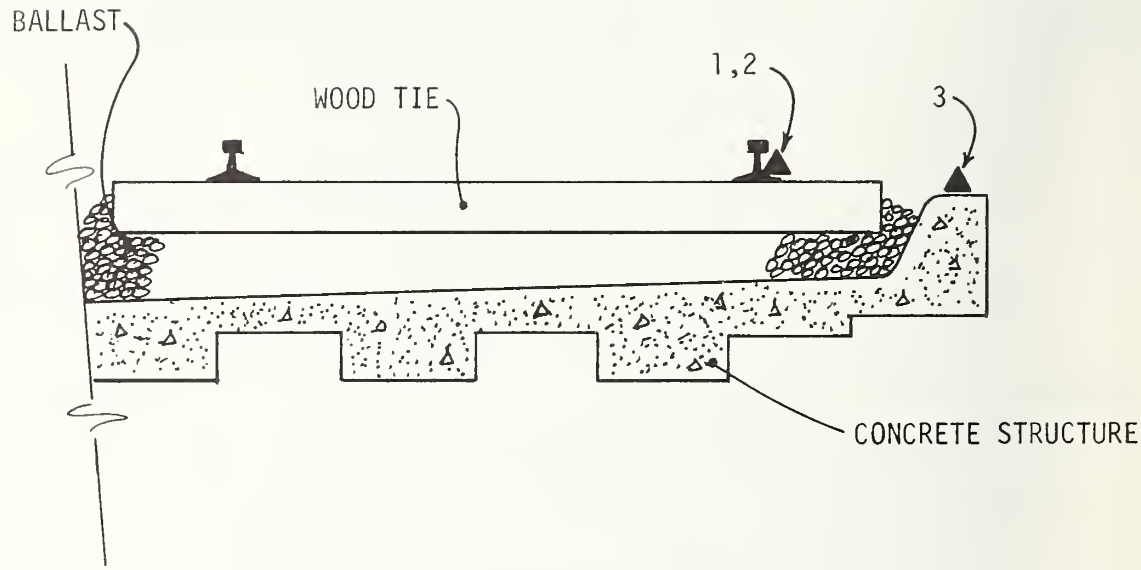


ACCELEROMETERS

1 RAIL, VERTICAL (DIRECT)
2 RAIL, VERTICAL (FM)
3 INVERT, VERTICAL (FM)
4 INVERT, LATERAL (FM)
5 BASEMENT, VERTICAL (FM)

I ACCELEROMETER PREAMPLIFIER
II SIGNAL CONDITIONING AMPLIFIER
III NAGRA IV SJ TAPE RECORDER

FIGURE 5-1. VIBRATION MEASUREMENT INSTRUMENTATION IN SUBWAY



▲ ACCELEROMETER LOCATIONS (ORIENTED VERTICALLY)

1 RAIL, FOOT (DIRECT)

2 RAIL, FOOT (FM)

3 STRUCTURE (FM)

FIGURE 5-2. ACCELEROMETER LOCATIONS ON ELEVATED STRUCTURE. ACCELEROMETERS WERE LOCATED MID-WAY BETWEEN TWO TIES

The equipment units used were Wilcoxon piezoelectric accelerometers, WIA unit gain accelerometer preamplifiers, WIA Model 222 2-channel signal conditioning amplifiers with frequency modulators, and NAGRA IV SJ tape recorders.

Using the FM record mode the instrumentation systems provide uniform frequency response from 1 Hz to 1500 Hz. In the direct analog record mode the instrumentation systems provide uniform frequency response from about 12 Hz to 14 kHz.

Accurate measurement of vibration of transit system facilities and equipment is often very difficult because of the sensitivity of the measurement equipment to electrical interference. This is particularly a problem when there is arcing between the contact shoe and the third rail or between the wheels and the running rail. Since the arcing typically creates a distinctive noise which accompanies the vibration signal on playback of the magnetic recording tapes, it is relatively simple to identify which passbys are contaminated by arcing. A significant percentage of the vibration data collected for this study was contaminated by arcing noise, however, all of the data reported herein are for passbys which were unaffected by arcing noise or other electrical interference.

The analysis of the field data collected on magnetic tapes was performed with an analysis system similar to that used for the acoustic data. Figure 5-3 is a block diagram of the data reduction system for the vibration data. The amplified signal from the tape recorder is input to the graphic level recorder and the real time analyzer. The trace on the graphic level recorder is used to determine the appropriate location on the tape for analysis of the vibration data sample. Typically, sample lengths of 2 to 4 seconds

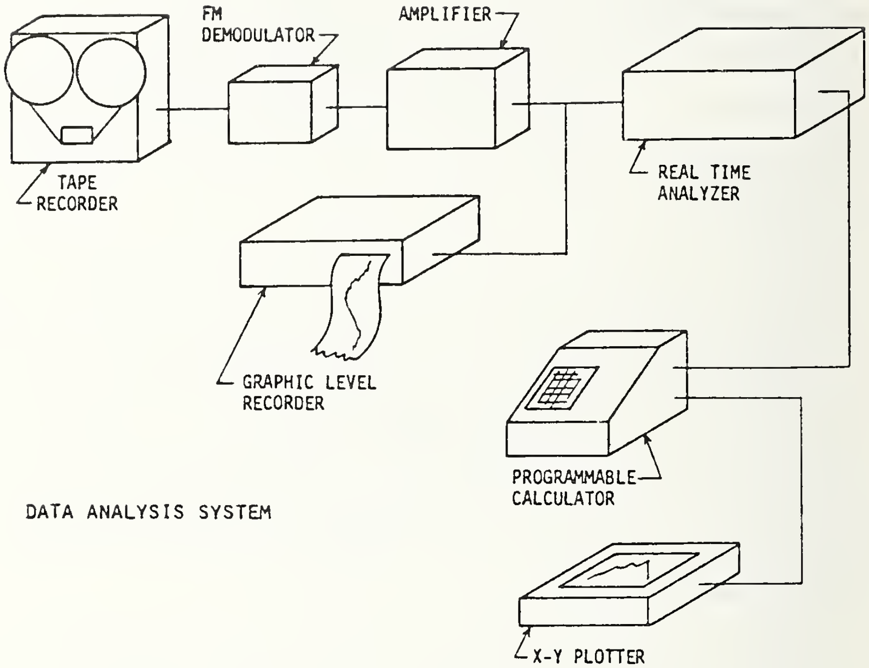


FIGURE 5-3. VIBRATION ANALYSIS EQUIPMENT

were used for the real time analysis. The acoustic data analysis procedures outlined in Interim Report #3 indicate the details of the analysis procedure for the acoustic data. For the vibration data a similar procedure and readout of 1/3 octave band levels was obtained. The only difference in the analysis procedure was that, with the vibration data, it was necessary to carefully evaluate each passby for contamination by electrical arcing noise and to eliminate those passbys where this noise interferred with obtaining valid data.

For most transit systems, the components of ground vibration above approximately 250 to 500 Hz rarely cause any problems but very low frequencies are significant. Hence, as indicated in Figures 5-1 and 5-2, the FM mode of signal conditioning and recording was used for most of the data collection to obtain low frequency data. Only the rail vertical vibration was recorded in the direct mode which in conjunction with the FM signal of the rail vertical vibration recorded on another channel provides a combined frequency response from 1 Hz to 12 kHz.

5.2 TEST RESULTS

The vibration data presented include measurements with Acousta Flex, Penn Bochum and SAB resilient wheels, all in new condition, and measurements with standard steel wheels worn by approximately one year of revenue service and recently trued standard steel wheels. Measurements were performed with all five test trains on recently ground welded rail in the subway (SUB 1) and on the elevated structure (TW). Also, the three resilient wheel trains were tested on the SUB 1 track with worn rails.

As discussed above, electrical interference contaminated a significant amount of the vibration data. Table 5-1 indicates the passby tests that were satisfactory and were used for the analysis of this section. The table includes the train speed for each run along with the measurement locations which gave useful data.

The vibration data requires considerably more complex analysis than the noise data since there is no generally valid single number metric, such as the A-weighted level for noise, that can be applied to vibration data. Because of this the vibration data are presented in this report in terms of averaged 1/3 octave band levels. Linear averages were performed using all of the valid passby data for each test condition. To help minimize the effects of speed variations, the average spectra have all been normalized to 60 km/hr. The normalizations were calculated using the assumption that the vibration is proportional to speed squared, which is equivalent to level being proportional to 20*log* (speed). The adjustment factor, ΔL, is given by the formula:

$$\Delta L = \frac{20}{n} \sum_{i=1} log \frac{60}{V_i}$$

where n = the number of samples

V_i = the train speed of the ith sample in km/hr.

Generally, the adjustments were 1 dB or less, the maximum adjustment being 3.5 dB when the only valid data were from one passby at 40 km/hr.

The adjusted averages for the various vibration test conditions are presented in Figures 5-4 through 5-13. The most striking features of these curves are the similarity of the results with the three sets of resilient wheels and the marked difference between the resilient wheel and conventional steel wheel results. There are two regions where the resilient wheel results show consistent variations. The first is between 31.5 Hz and 100 Hz where the vibration levels with SAB wheels are several dB lower than with the Acousta Flex and Penn Bochum wheels. See for example Figures 5-4, 5-5 and 5-7. The largest variation is 12 dB in the 63 Hz 1/3 octave band for the vertical vibration of the elevated structure. Some difference occurred at every measurement location except on the rail in the subway. This difference is due to the greater resilience of the SAB wheels compared to the Acousta Flex and Penn Bochum wheels and has been observed for similar tests at other transit systems.

Another interesting result with the resilient wheels is the dip in vibration level in the 500 Hz range exhibited by the Penn Bochum wheels. The dip occurs for all of the test conditions and typically results in vibration level for the Penn Bochum wheels being 5 to 10 dB lower than for the other resilient wheels in the 500 Hz 1/3 octave. Since transit system vibration problems generally occur at frequencies well below 500 Hz, a reduction in vibration level around 500 Hz will not provide significant benefits for ground-borne vibration but may indicate benefit for airborne noise from wheel/rail vibration.

Figures 5-14 and 5-15 present the vibration levels with trued wheels relative to the worn standard steel wheels and new resilient wheels relative to trued wheels. In most cases the levels with worn wheels were significantly higher than with trued or resilient wheels. The data indicate that wheel truing and use of resilient wheels will reduce the ground-borne vibration levels by a significant degree. A factor that contributed to the relatively high vibration levels observed with the worn steel wheels was the presence of wheel flats. Although the flats were not clearly identifiable on the wheel surface and did not create noticeable airborne noise, the presence of flats was evident in the vibration signals. To a lesser degree, some wheel flat noise was evident on several of the vibration tests with the trued standard wheels.

Between approximately 31.5 and 63 Hz the trued standard wheels created higher vibration levels than the worn wheels at several of the measurement locations. These higher levels may have been caused by differences in the wheel condition, however it is likely that they are a result of differences in the resilience of the truck axle to frame supports or journal bearing sleeves.

Figure 5-16 presents the differences between the levels observed at the subway test track before and after rail grinding. Although the data do not indicate any reduction at the rail, above 63 Hz the subway invert and basement vibration levels were both reduced. Above 125 Hz the reduction averaged just over 5 dB.

TABLE 5-1. LISTING OF VIBRATION TEST RUNS - SPEED AND LOCATION FOR EACH TEST CONDITION

Wheel Type	Run Number	Speed km/hr	Location* 1	2	3	4	5
SUBWAY - WORN WELDED RAIL October 3, 1976:							
Acousta Flex (Cars 628/645)	1	44	X	X	X	X	X
	2	56	X	X	X	X	X
	3	34	X	X	X	X	X
	4	54	X	X	X	X	X
	5	33	X	X	X	X	X
	6	52	X	X	X	X	X
Penn Bochum (Cars 626/631	1	65			X	X	X
	2	58			X	X	X
	3	67			X	X	X
	4	45	X		X	X	X
	5	43			X	X	X
	6	55			X	X	X
	7	42			X	X	X
	8	66			X	X	X
	9	53	X	X	X	X	X
	10	46	X	X	X	X	X
	11	38			X	X	X
	12	67	X	X	X	X	X
	13	55	X	X		X	X

*See Figure 5-1 for description of accelerometer locations.

TABLE 5-1. (CONT.)

Wheel Type	Run Number	Speed km/hr	Location* 1	2	3	4	5
SUBWAY — WORN WELDED RAIL		October 3, 1976 (cont.):					
SAB (Cars 609/630)	1	59	X	X	X	X	X
	2	59	X	X	X	X	X
	3	68	X	X	X	X	X
	4	74					X
	5	48	X	X	X	X	X
	6	44	X	X	X	X	X
	7	75	X		X	X	X
SUBWAY — GROUND WELDED RAIL		October 15, 1976:					
Worn Standard (Cars 613/623)	1	50	X	X	X		X
	2	64	X	X			X
	3	67	X	X	X		X
	4	80	X	X	X		X
	5	45	X	X	X		
	6	41	X	X	X		X
	7	62	X	X	X		X
New Standard (Cars 755/756)	1	59	X	X	X	X	X
	2	60					
	3	69	X	X		X	X
	4	78		X	X		X
	5	47	X	X	X		X
	6	42	X	X	X		X

*See Figure 5-1 for description of accelerometer locations.

TABLE 5-1. (CONT.)

Wheel Type	Run Number	Speed km/hr	Location* 1	2	3	4	5
SUBWAY — GROUND WELDED RAIL October 15, 1976 (cont.):							
Acousta Flex (Cars 628/645)	1	59		X			X
	2	56	X	X			X
	3	55	X	X			X
	4	65	X	X	X		X
	5	48		X	X	X	X
	6	40	X	X	X	X	X
Penn Bochum (Cars 626/631)	1	51	X	X	X	X	X
	2	58		X			X
	3	56	X	X	X	X	X
	4	76		X			
	5	40		X	X		X
	6	42		X	X		X
SAB (Cars 609/630)	1	61	X				X
	2	58					X
	3	69	X				X
	4	76	X				X
	5	41	X		X	X	X
	6	44			X		X

*See Figure 5-1 for description of accelerometer locations.

TABLE 5-1. (CONT.)

Wheel Type	Run Number	Speed km/hr	Location* 1	2	3
ELEVATED STRUCTURE — GROUND WELDED RAIL October 4, 1976:					
Worn Standard (Cars 613/623)	1	59	X		X
	2	41	X	X	X
New Standard (Cars 755/756)	1	40		X	X
	2	82	X		
	3	61		X	X
	4	79	X		X
	5	61	X		X
	6	42	X	X	X
Acousta Flex (Cars 628/645)	1	54	X	X	X
	2	67	X		X
	3	56	X	X	X
	4	67	X		X
	5	39	X	X	X
	6	43	X	X	X
Penn Bochum (Cars 626/631)	1	42	X	X	X
	2	69	X		X
	3	60	X	X	X
	4	70	X		X
	5	60	X		X
	6	43	X	X	X

*See Figure 5-2 for description of accelerometer locations.

TABLE 5-1. (CONT.)

Wheel Type	Run Number	Speed km/hr	Location* 1	2	3
ELEVATED STRUCTURE - GROUND WELDED RAIL October 4, 1976 (cont.)					
SAB (Cars 609/630)	1	59	X	X	X
	2	76	X	X	X
	3	60	X	X	X
	4	80	X		X
	5	40	X	X	X
	6	42	X	X	X

*See Figure 5-2 for description of accelerometer locations.

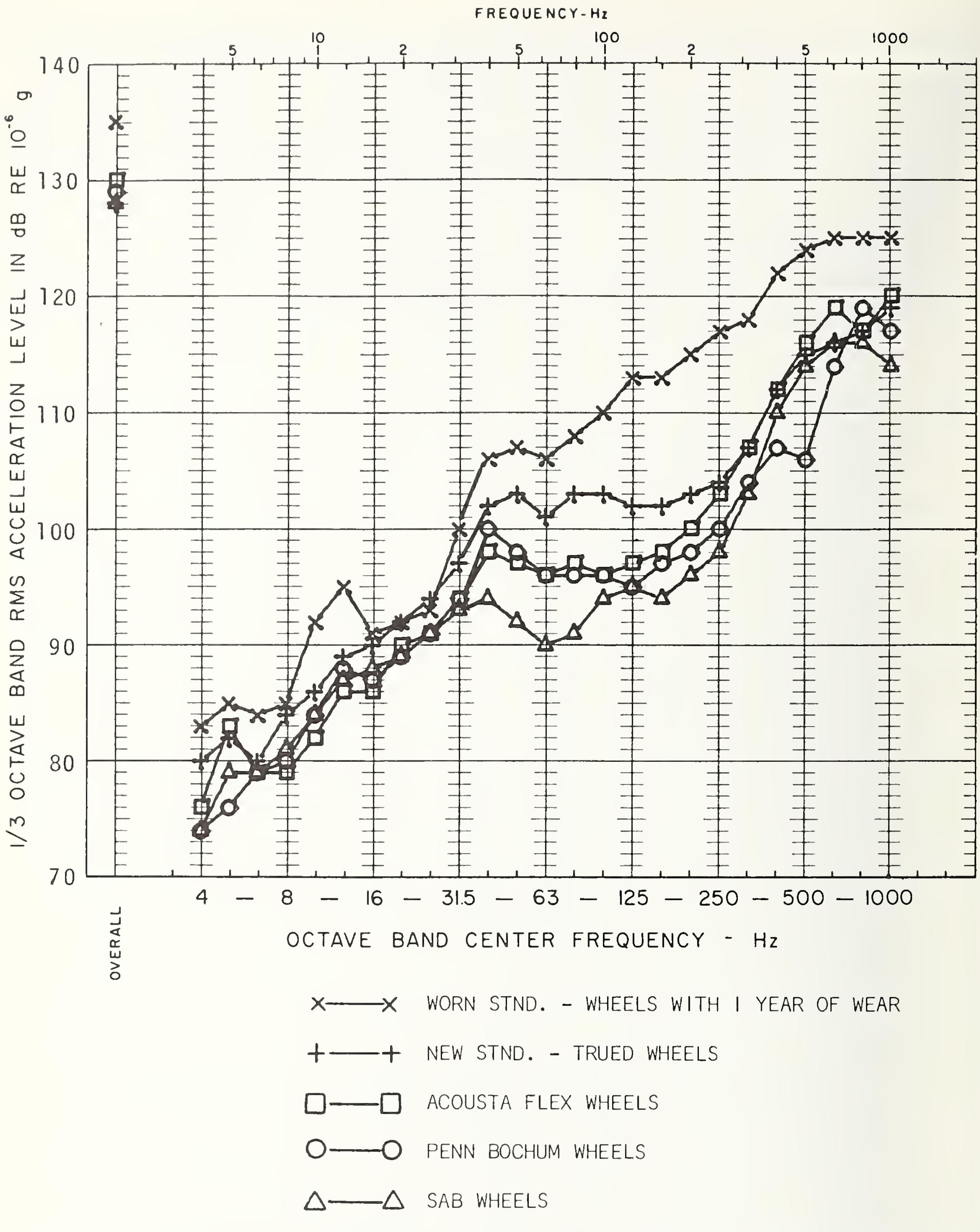


FIGURE 5-4. AVERAGE VERTICAL VIBRATION SPECTRA OF RAILS - TW TEST TRACK

PHASE IIA - GROUND RAILS

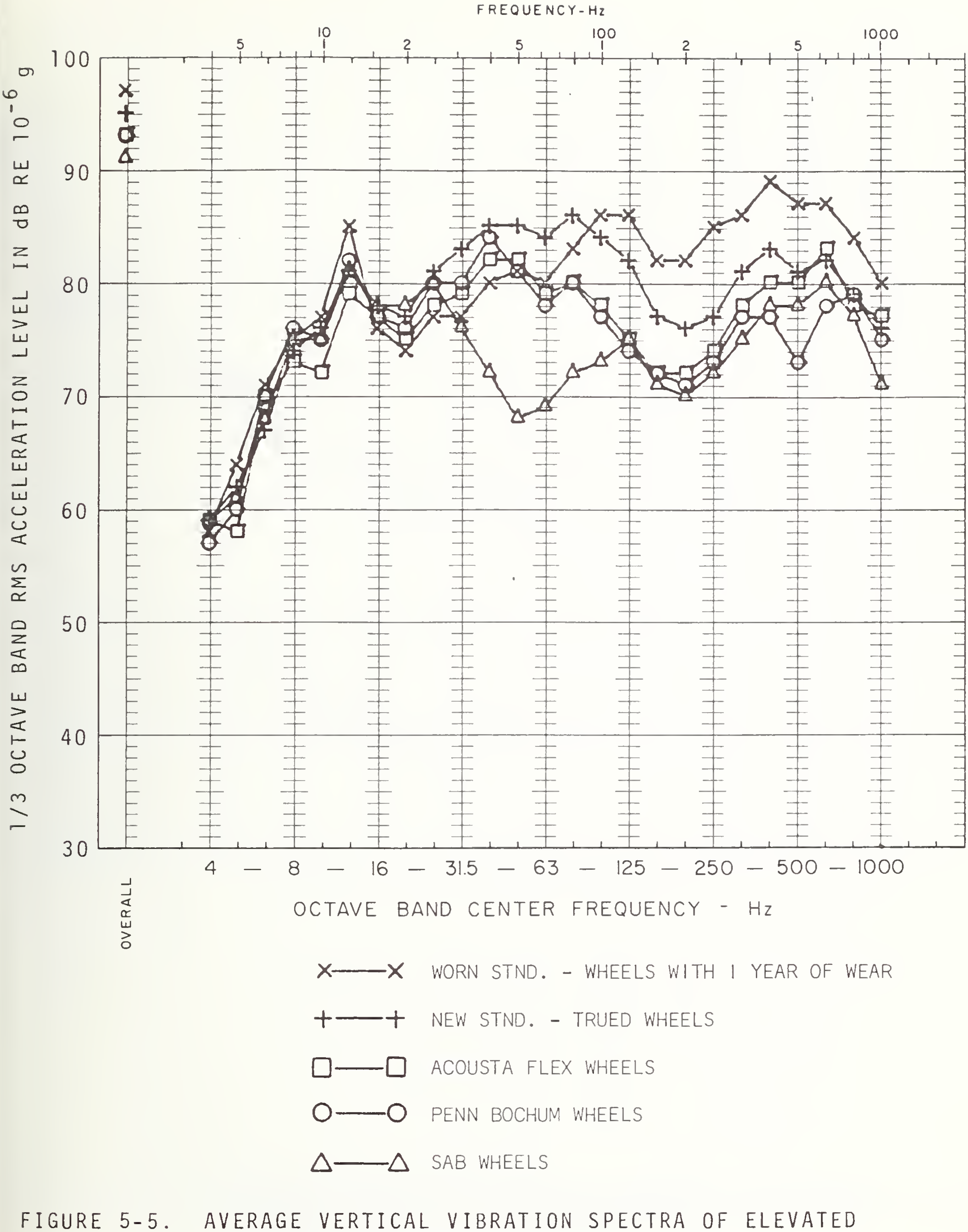


FIGURE 5-5. AVERAGE VERTICAL VIBRATION SPECTRA OF ELEVATED STRUCTURE, TW TEST TRACK

PHASE IIA - GROUND RAILS

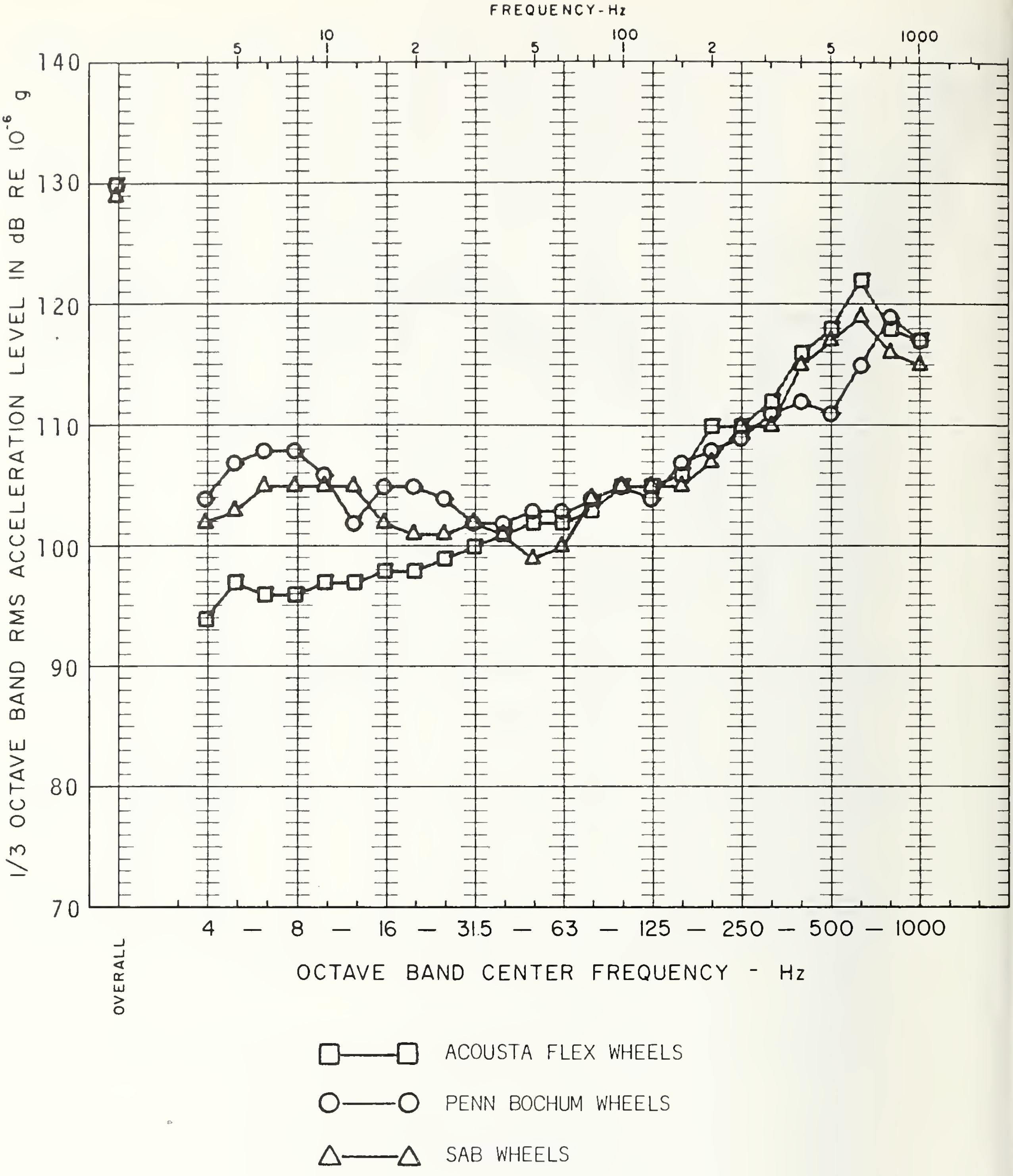


FIGURE 5-6. AVERAGE VERTICAL VIBRATION SPECTRA OF RAIL - SUBWAY TEST TRACK, TANGENT WELDED RAIL

PHASE IIA - WORN RAILS

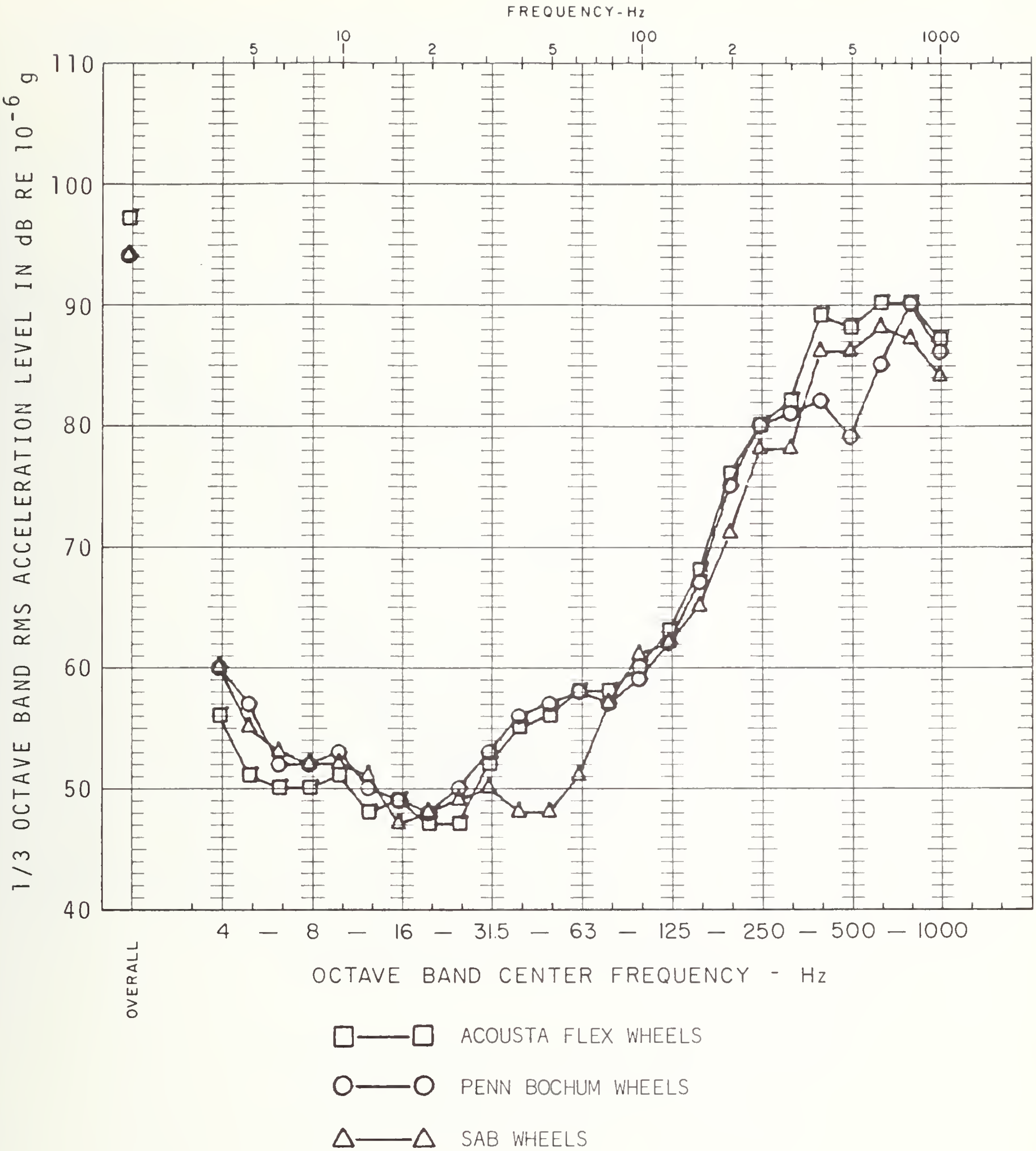


FIGURE 5-7. AVERAGE VERTICAL VIBRATION SPECTRA AT INVERT - SUBWAY TEST TRACK, TANGENT WELDED RAILS

PHASE IIA - WORN RAIL

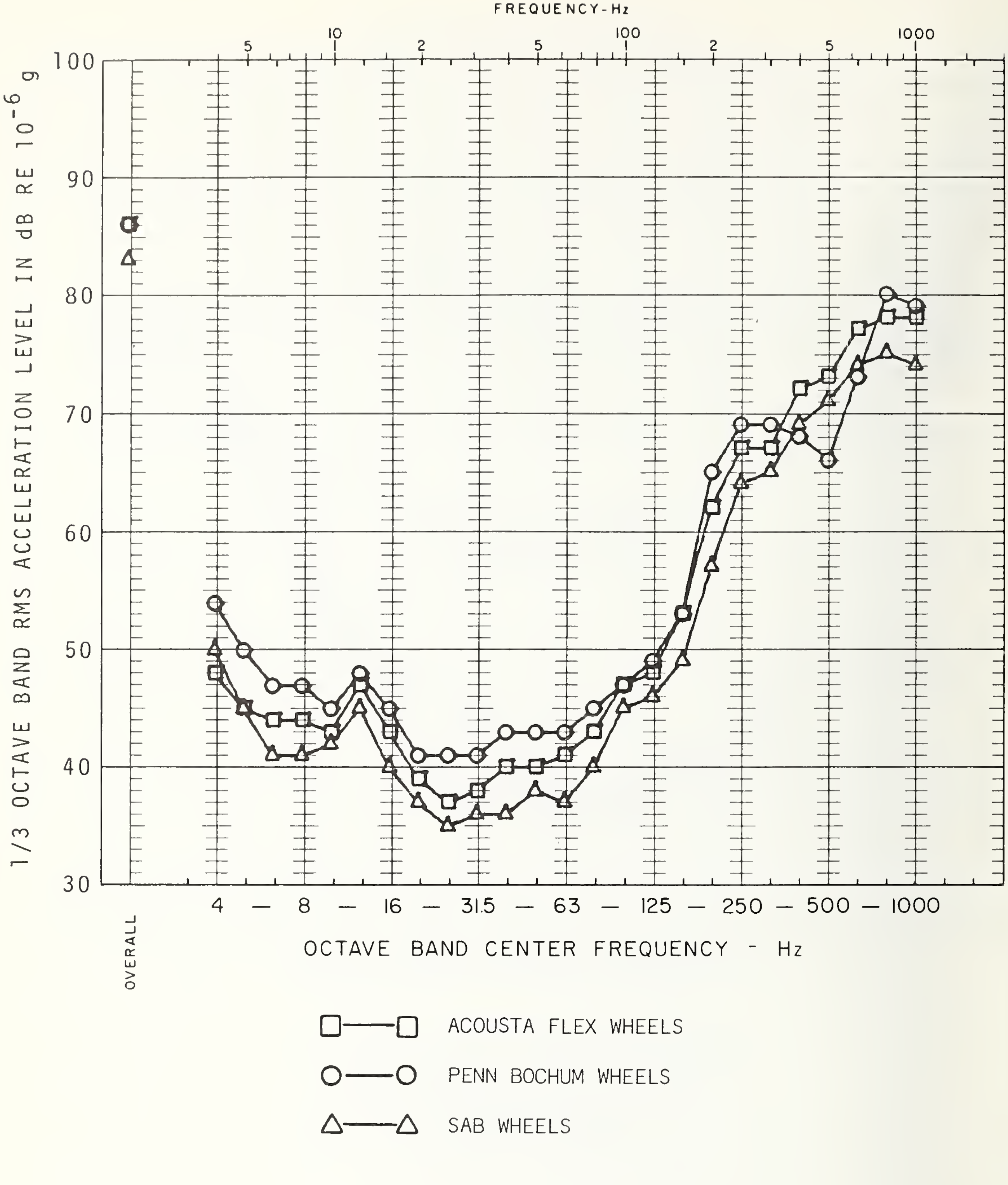


FIGURE 5-8. AVERAGE LATERAL VIBRATION SPECTRA AT INVERT - SUBWAY TEST TRACK, TANGENT WELDED RAILS

PHASE IIA - WORN RAILS

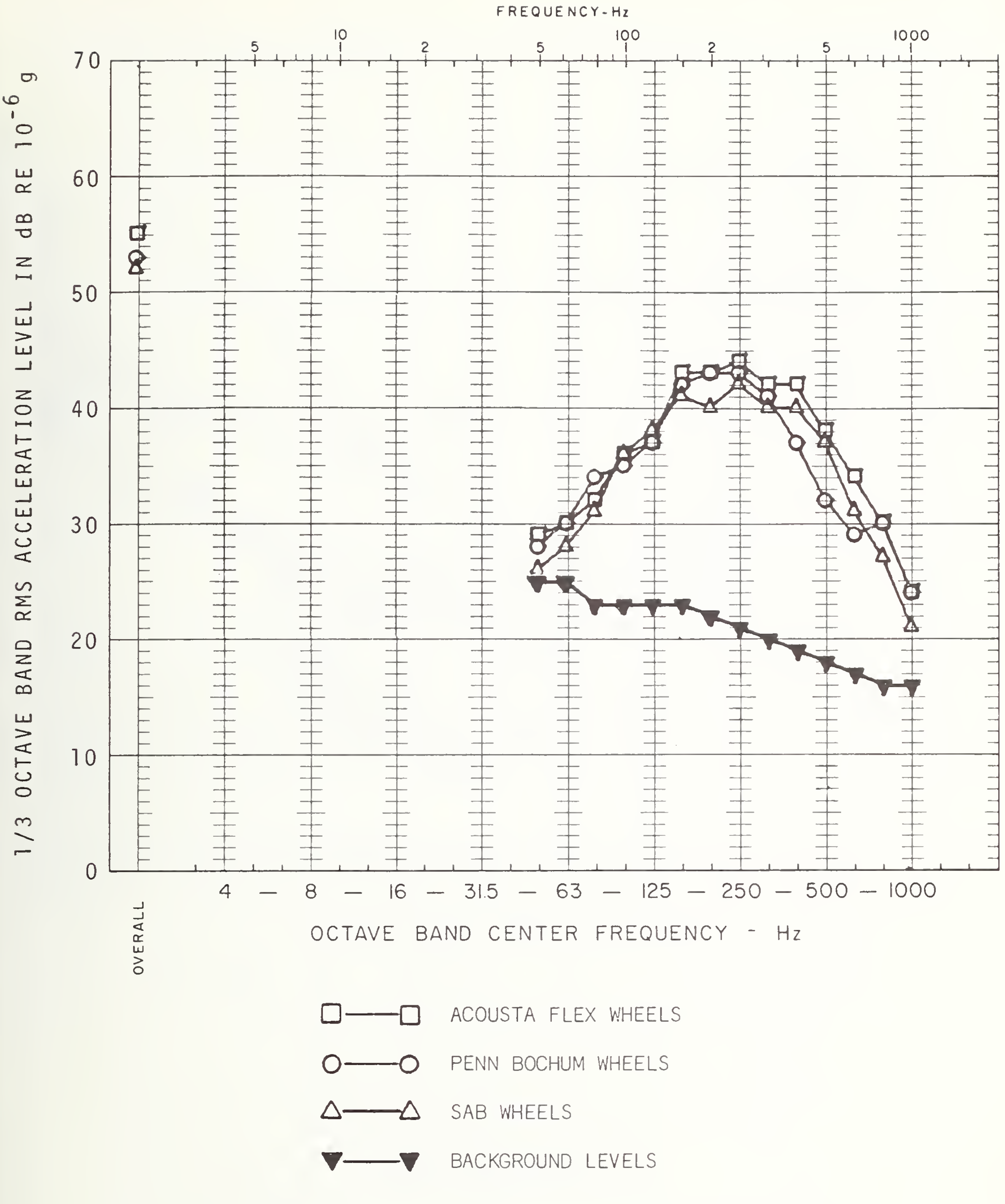


FIGURE 5-9. AVERAGE VERTICAL VIBRATION SPECTRA OF BASEMENT FLOOR - SUBWAY TEST TRACK, TANGENT WELDED RAIL

PHASE IIA - WORN RAILS

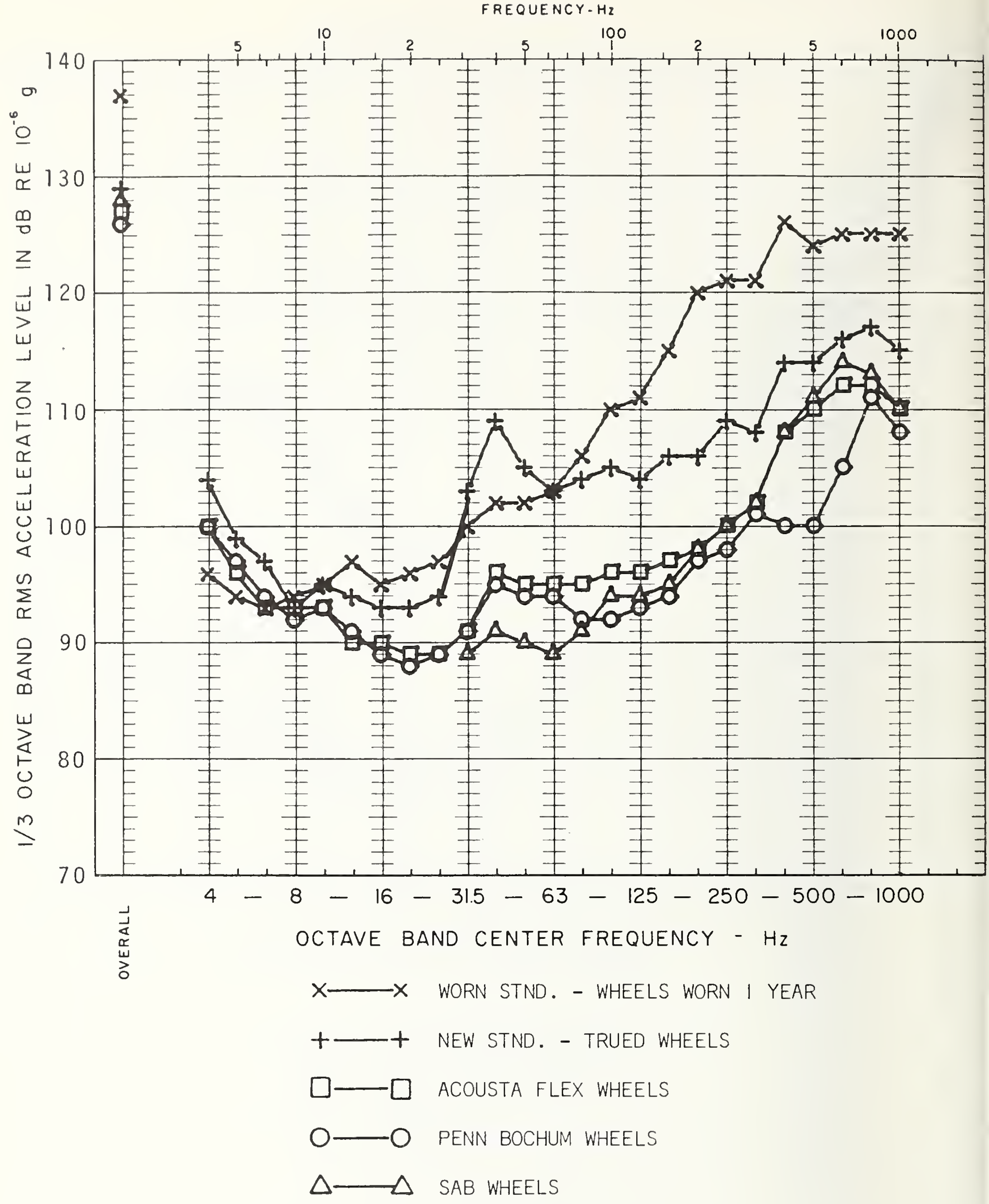


FIGURE 5-10. AVERAGE VERTICAL VIBRATION SPECTRA OF RAIL - SUBWAY TEST TRACK, TANGENT WELDED RAILS

PHASE IIB - GROUND RAILS

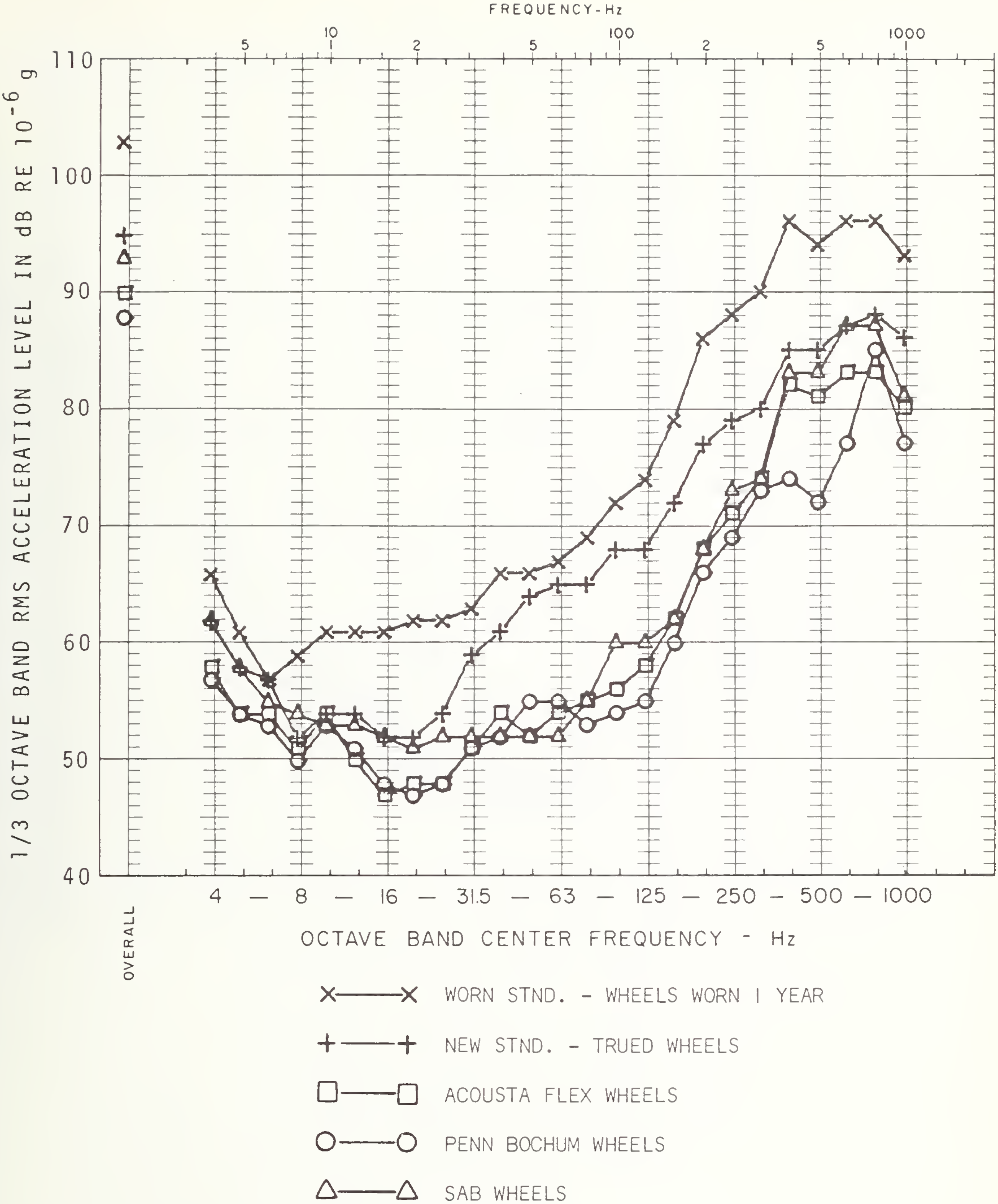


FIGURE 5-11. AVERAGE VERTICAL VIBRATION SPECTRA AT INVERT - SUBWAY TEST TRACK, TANGENT WELDED RAILS

PHASE IIB - GROUND RAILS

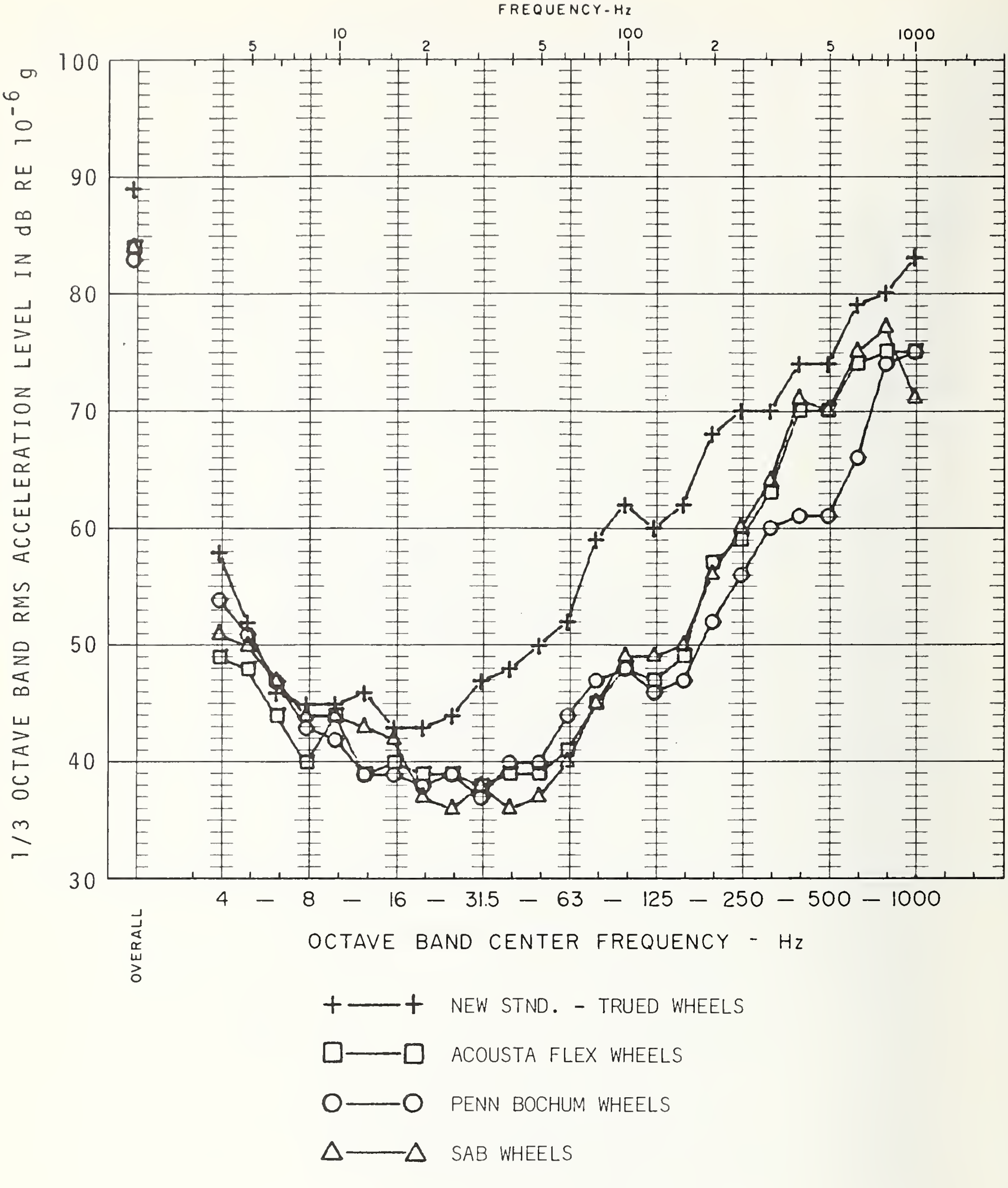


FIGURE 5-12. AVERAGE LATERAL VIBRATION SPECTRA AT INVERT - SUBWAY TEST TRACK, TANGENT WELDED RAILS

PHASE IIB - GROUND RAILS

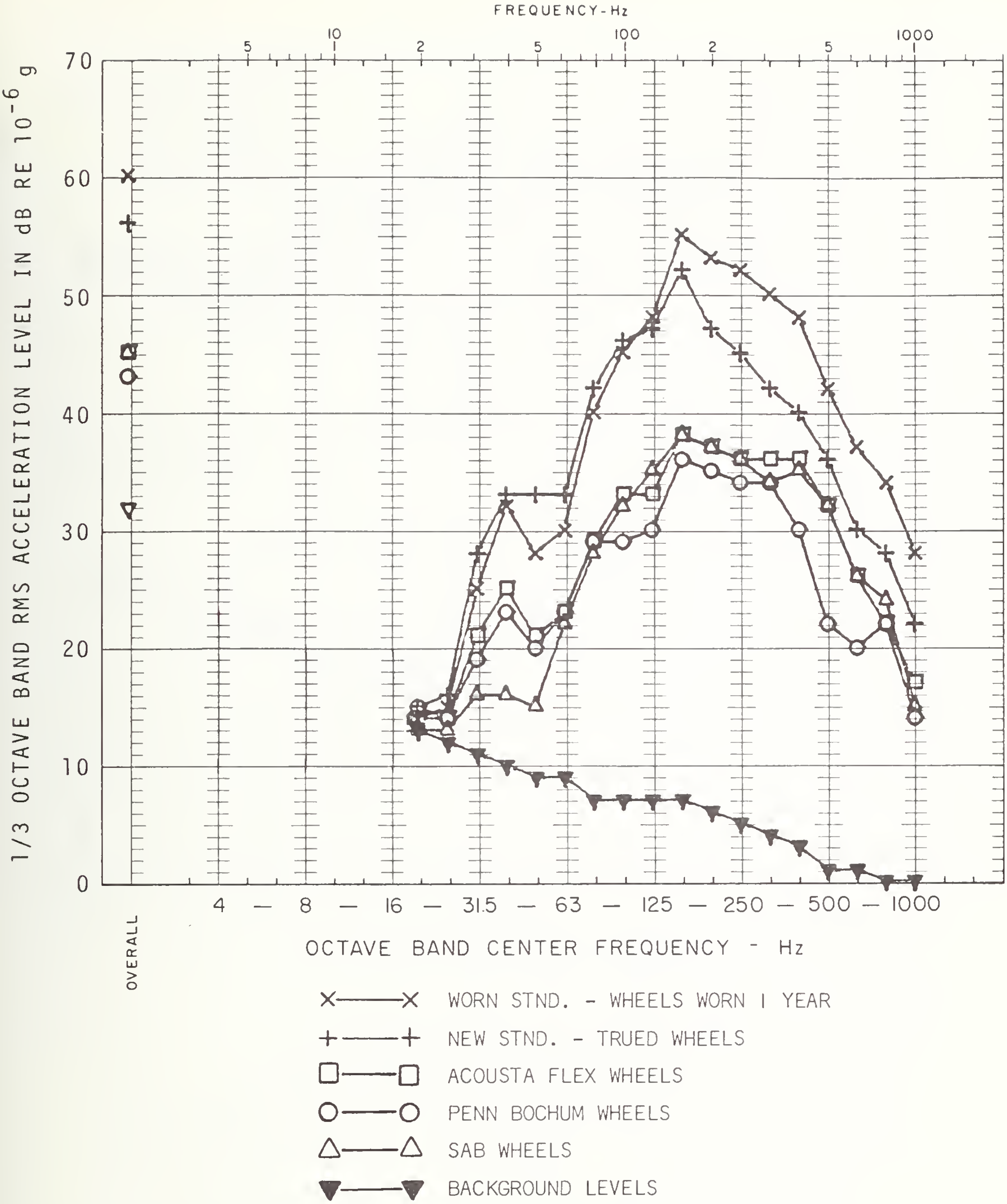


FIGURE 5-13. AVERAGE VERTICAL VIBRATION SPECTRA AT BASEMENT LOCATION - SUBWAY TEST TRACK, TANGENT WELDED RAIL

PHASE IIB - GROUND RAILS

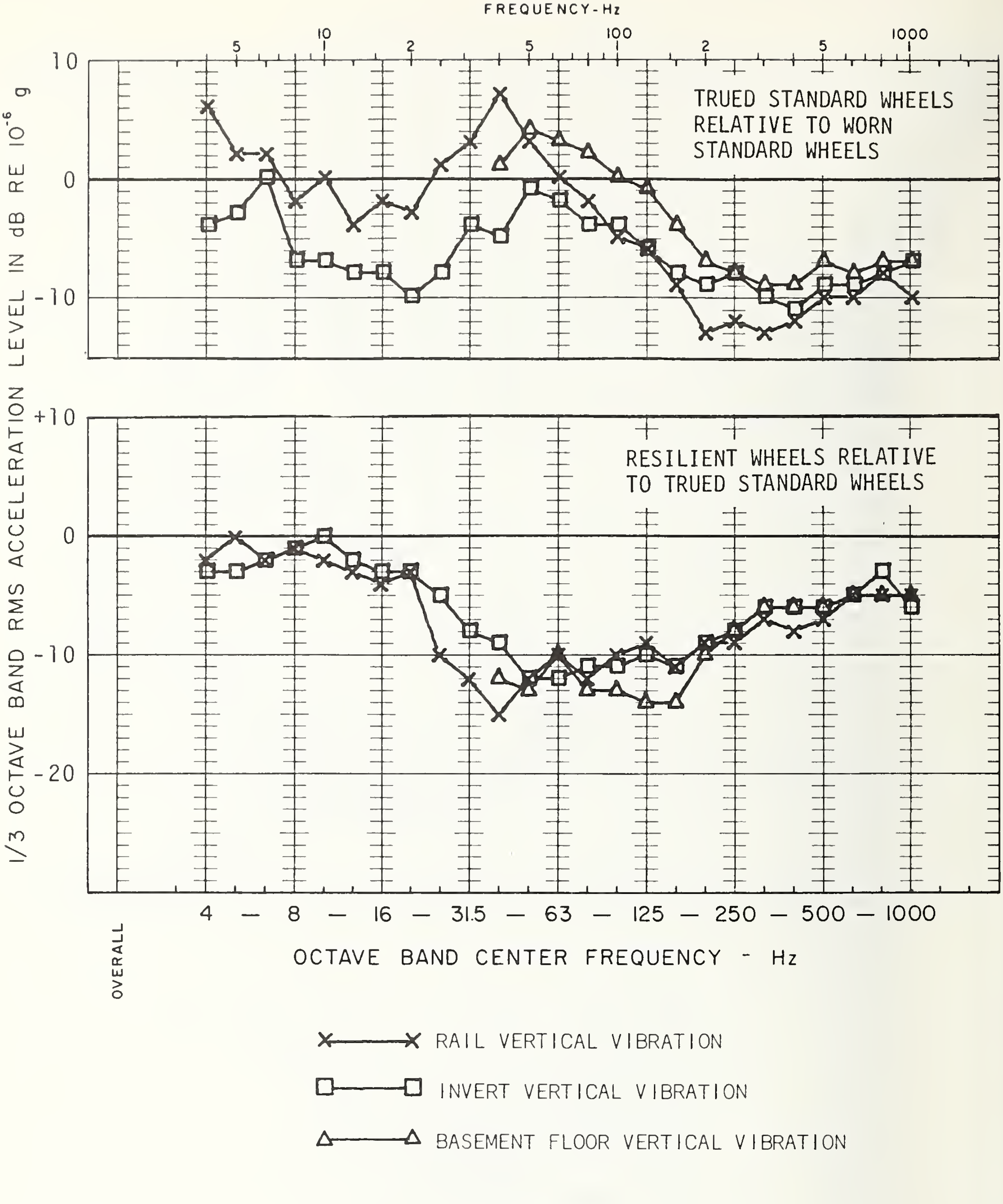


FIGURE 5-14 AVERAGE VIBRATION SPECTRA FOR TRUED STANDARD WHEELS RELATIVE TO WORN STANDARD WHEELS AND FOR NEW RESILIENT WHEELS RELATIVE TO TRUED STANDARD WHEELS - SUBWAY TEST TRACK, GROUND WELDED RAILS

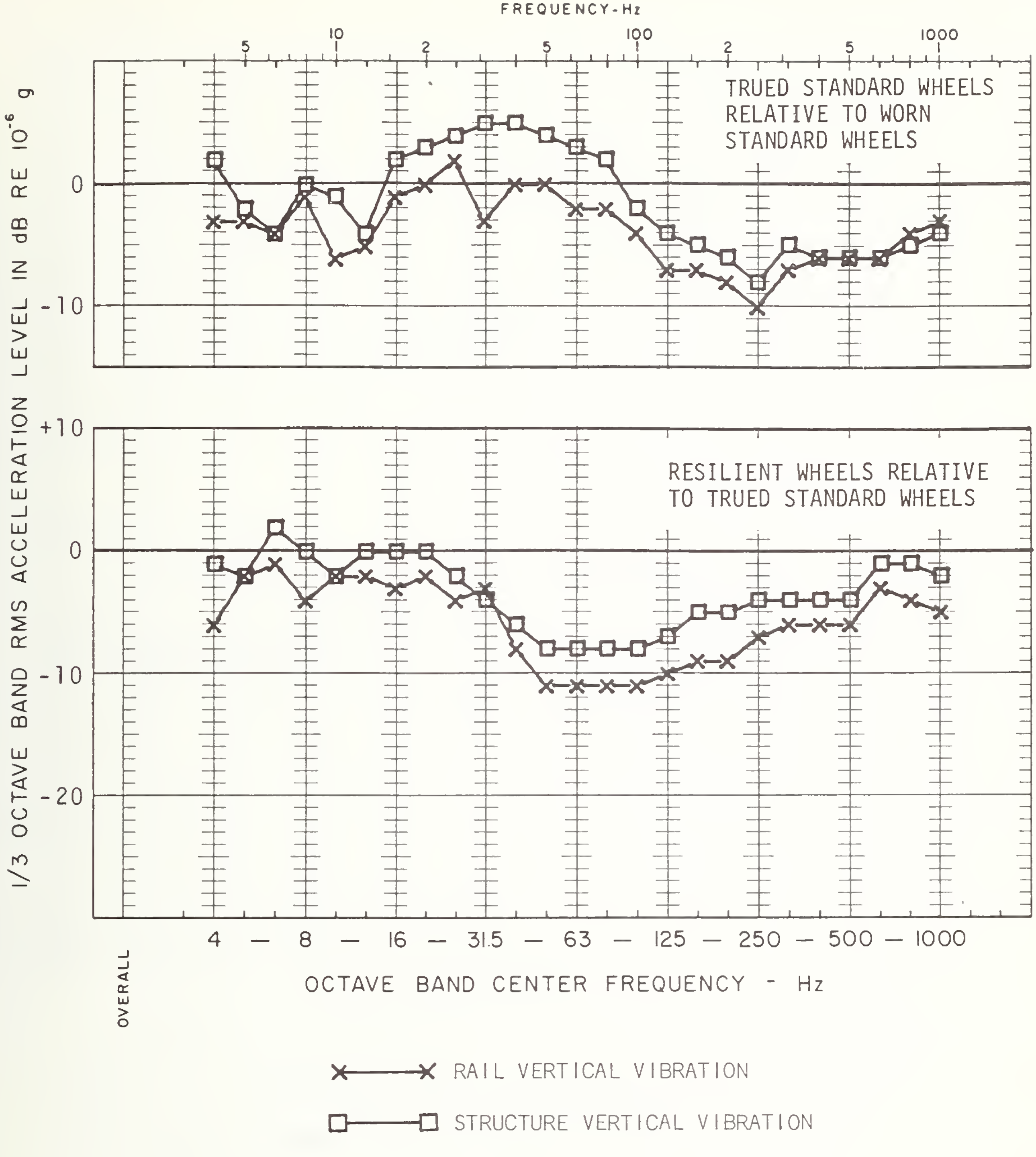


FIGURE 5-15 AVERAGE VIBRATION SPECTRA FOR TRUED STANDARD WHEELS RELATIVE TO WORN STANDARD WHEELS AND FOR NEW RESILIENT WHEELS RELATIVE TO TRUED STANDARD WHEELS - TW TEST TRACK, GROUND RAILS

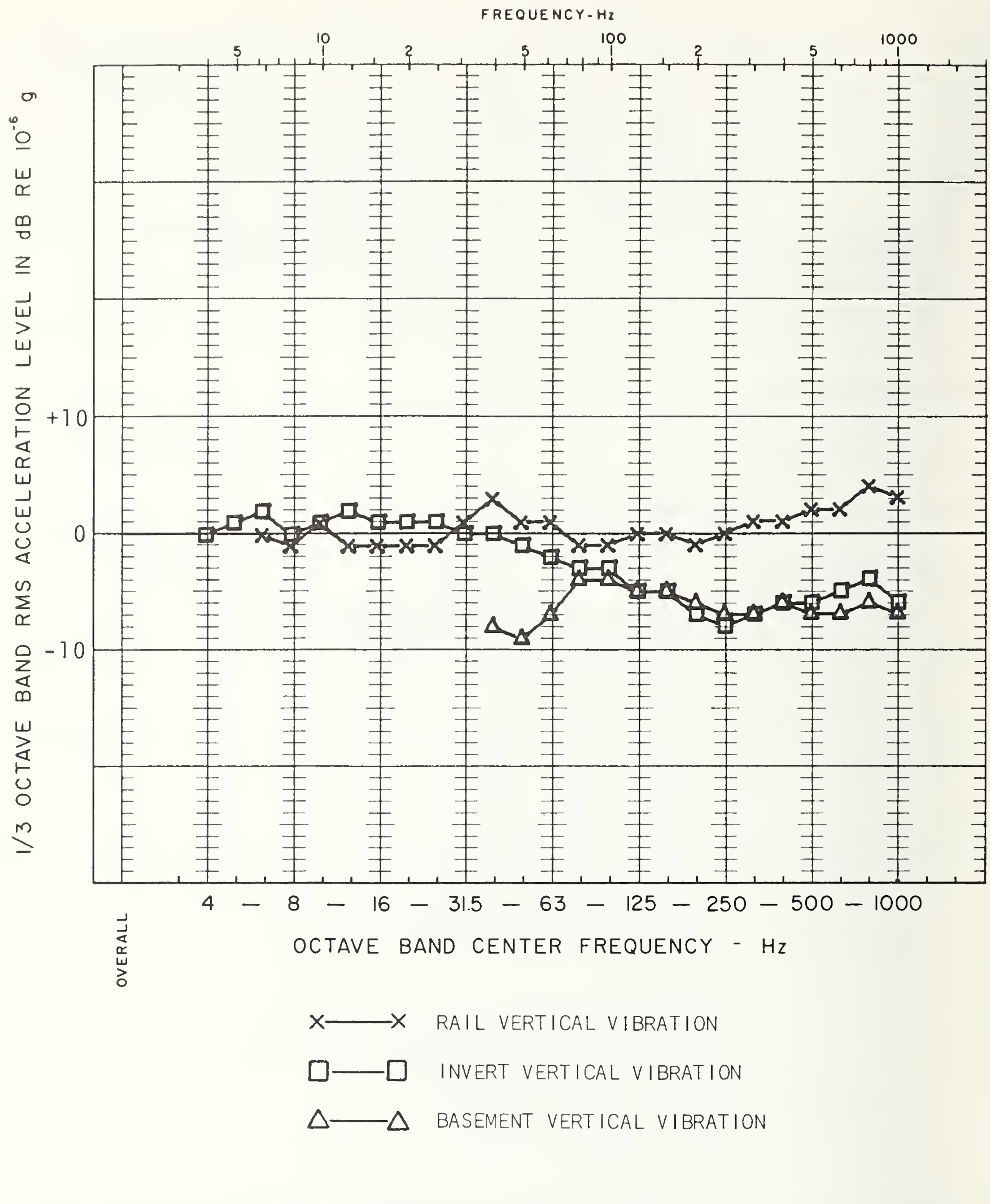


FIGURE 5-16. AVERAGE VIBRATION SPECTRA FOR RECENTLY GROUND RAILS RELATIVE TO WORN RAILS - SUBWAY TEST TRACK, TANGENT WELDED RAILS

6. WHEEL DECAY RATE TEST RESULTS

The internal damping of transit wheels has a strong influence on the generation of wheel squeal noise and some effect on roar noise. A simple series of tests was performed to evaluate the damping loss factors of the test wheels by measuing the vibration decay rate. The method used was found to generate consistent results and to correlate well with similar tests that have been performed by others.

6.1 TEST PROCEDURES

The apparatus used to measure the vibration decay rate is shown in Figure 6-1. The test wheel was impacted with a hammer and the resulting vibration decay detected by accelerometers at two locations and recorded on a precision tape recorder. The tapes were then played back through an octave band filter and the vibration decay for each impact recorded on a strip chart for the 500 Hz through 8000 Hz octave bands.

The impact from a steel hammer was found to excite all frequencies above approximately 250 Hz. For each wheel, 10 to 15 impacts at various locations on the wheel rim and web were recorded.

A total of 11 tests were performed; the testing sequence is summarized in Table 6-1. Tests were performed with two of each type of the resilient wheels, three ring-damped wheels, and one standard steel wheel. All of the tests except numbers 6 and 7 were performed with the wheels suspended from a steel bar that was inserted through the axle hole. Tests 6 and 7 were performed on wheels already

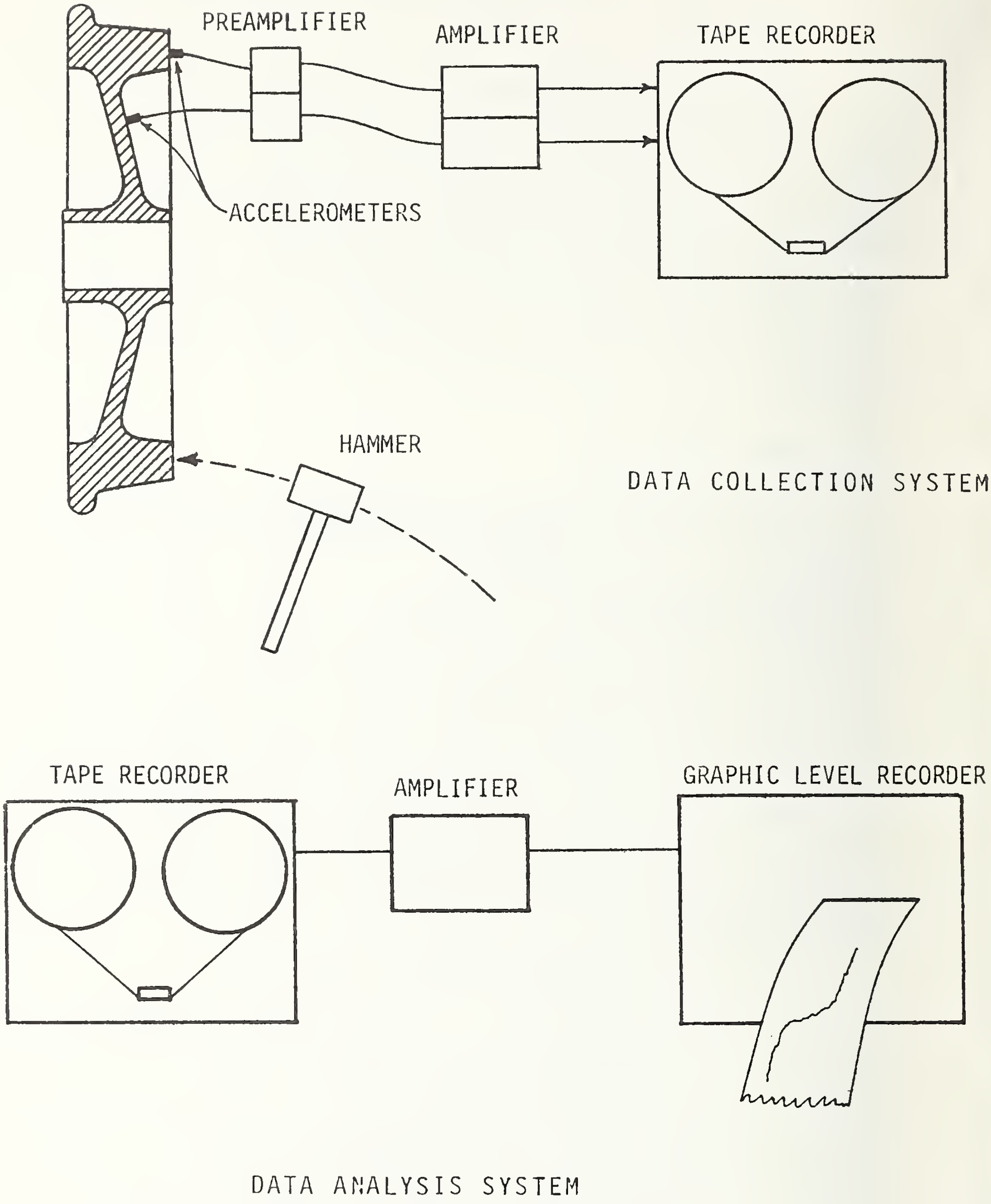


FIGURE 6-1. WHEEL VIBRATION DECAY MEASUREMENT SYSTEM

TABLE 6-1. SUMMARY OF WHEEL VIBRATION DECAY TESTS

Test Wheel	Test Number	Serial Number	Comments
Penn Bochum #1	1	23243	
Acousta Flex #1	2	05Y126?	
Ring-Damped #1	3	576Z 1000926	
Standard	4	576Z 1000926	Grooved standard wheel without ring-damper
Ring-Damped #2	5	576Z 1000926	Damping ring removed and replaced
Ring-Damped #3	6	G2701313	On Car 644
Ring-Damped #4	7	G147555	On Car 607
SAB #1	8	33135	
Penn Bochum #2	9	23246	
SAB #2	10	33133	
Acousta Flex #2	11	05Y1267	

mounted on transit cars. The cars were on jacks with the wheels freely suspended and the brake shoes backed off.

Note that tests 3, 4 and 5 were performed with the same wheel - a wheel that had been grooved for ring-dampers. First the wheel was tested with the ring-damper installed, then a test was made with the ring-damper removed, and a final test was done with the ring-damper reinstalled. With the damping ring removed the wheel is virtually identical to normal steel wheels and, as is typical for undamped steel wheels, the ringing was audible for 4 to 5 seconds.

Typical examples of the vibration decay curves are shown in Figure 6-2. The rate of decay was approximated with a best fit straight line, the slope of which was used to determine the loss factor using the formula:

$$\eta = \frac{\Delta}{27.3\ f_n}$$

where η = loss factor

Δ = decay rate, dB/sec

f_n = octave band center frequency.

Note that loss factor is one of many different quantities that are commonly used to define damping. The relationships between these quantities are given in a number of basic textbooks, e.g., Reference 6, page 439.

Figure 6-2 presents some of the typical decay curves. In evaluating the loss factor, an effort was made to obtain the best fit straight lines for the decay curves. Examples such as Figure 6-2a are well represented by a straight line decay. Figures 6-2b, 6-2c and 6-2d are examples of decay curves requiring some subjective judgment in estimating the

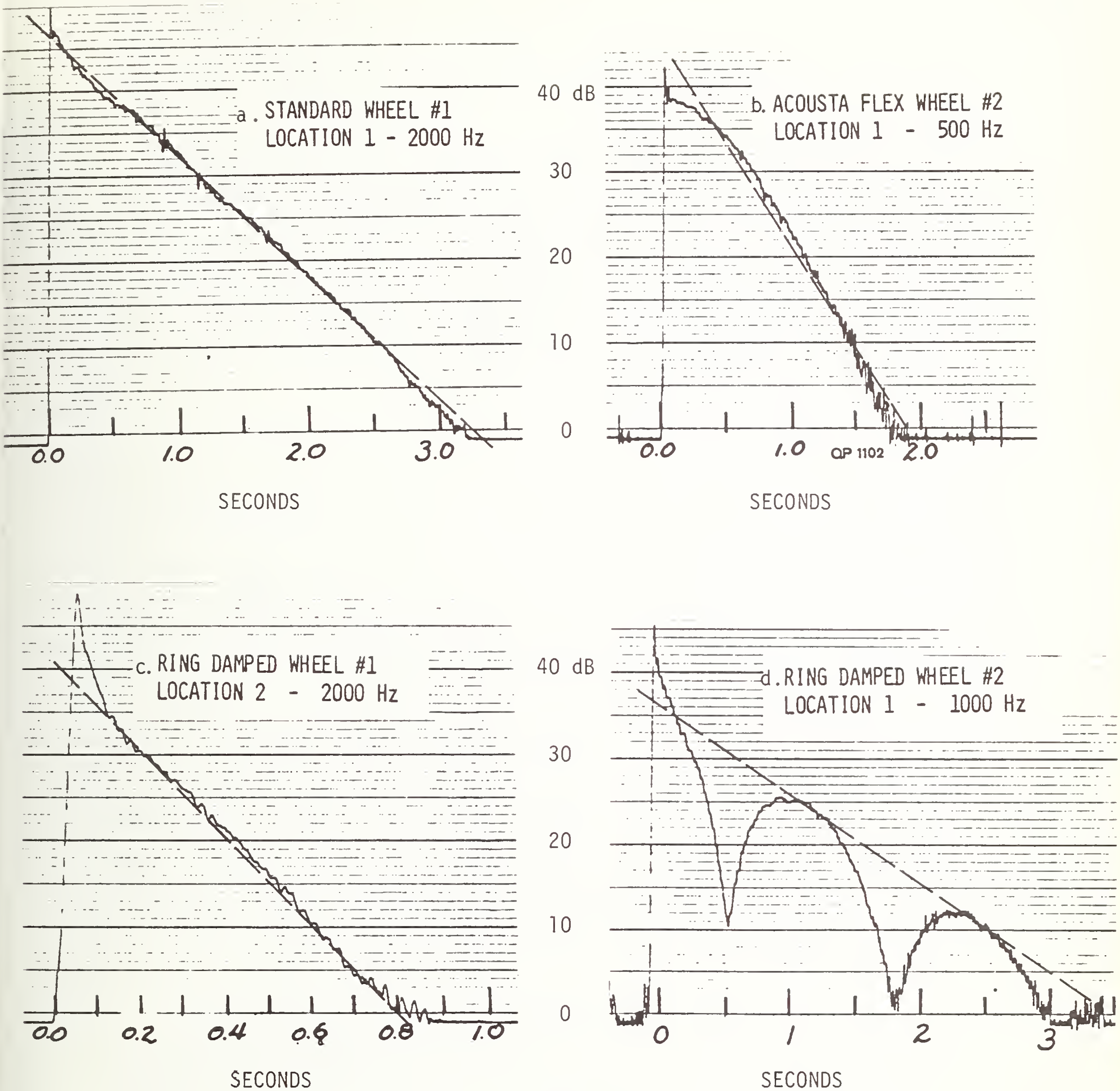


FIGURE 6-2 TYPICAL VIBRATION DECAY CURVES

decay curve as a straight line. The straight lines used are shown in the figures. For examples such as Figure 6-2c with a double sloped decay curve, the longest duration slope was used.

In several cases a strong beating characteristic was displayed in the decay curve. Figure 6-2d is an example of strong beating with a beat period of approximately 1.2 seconds. The beating is most likely to be caused by exciting two separate normal modes that have natural frequencies that are very close. In these cases the decay rate of the beat envelope was used for the analysis.

6.2 DECAY RATE RESULTS

The decay rate results for the 11 wheels that were tested are given in Table 6-2 in terms of the average loss factor. For comparison, the results of similar tests that were performed by N. Perfect of the Testing and Instrumentation Laboratory of the Ontario Ministry of Transportation and Communication[7] are presented in Table 6-3.

The Ontario study investigated the vibration characteristics of Toronto Transit Commission (TTC) conventional steel and SAB and Penn Bochum resilient wheels in some detail. They studied the shapes, natural frequencies, and the decay rates of specific modes of the three wheels. The decay rate of an individual mode was investigated by tuning a notch filter to a natural frequency and recording the vibration decay.

The results of the vibration decay tests are shown graphically on Figure 6-3. This graph illustrates that even though the test procedures were different, the results of this study and the Ontario study closely correspond.

TABLE 6-2. AVERAGE LOSS FACTORS ($\eta \times 10^3$) FOR SEPTA TEST WHEELS

Wheel Type	Octave Band Center Frequency (Hz)				
	500	1000	2000	4000	8000
Standard	0.70	0.37	0.29	0.14	0.14
Penn Bochum #1	11.	10.	5.2	3.7	3.4
#2	12.	18.	9.2	4.2	3.4
Average	12.	14.	7.2	4.0	3.4
Acousta Flex #1	22.	9.2	5.0	3.7	2.8
#2	2.0	0.92	6.1	3.1	3.4
Average	12.	5.1	5.6	3.4	3.1
SAB #1	2.9	1.5	0.73	0.55	0.65
#2	2.4	1.8	1.0	0.86	0.47
Average	2.6	1.6	0.87	0.70	0.56
Ring-Damped #1	0.77	0.34	1.4	0.66	0.33
#2	0.79	0.39	1.6	1.8	1.20
#3 on Car	1.10	0.52	3.3	1.5	0.46
#4 on Car	0.85	0.42	1.3	1.4	0.57
Average	0.85	0.42	1.9	1.3	0.64

TABLE 6-3. LOSS FACTORS FROM TTC STUDY[7]

Wheel Type	Frequency	Loss Factor ($\eta \times 10^3$)
Standard	620	0.64
	1580	0.28
	2750	0.15
	3990	0.084
	5280	0.082
	6250	0.082
Penn Bochum	434	10.2
	1240	6.2
	2200	16.6
	4600	9.6
SAB	433	4.8
	1190	2.2
	2100	1.7
	3070	1.6
	4090	1.0
	5160	0.78

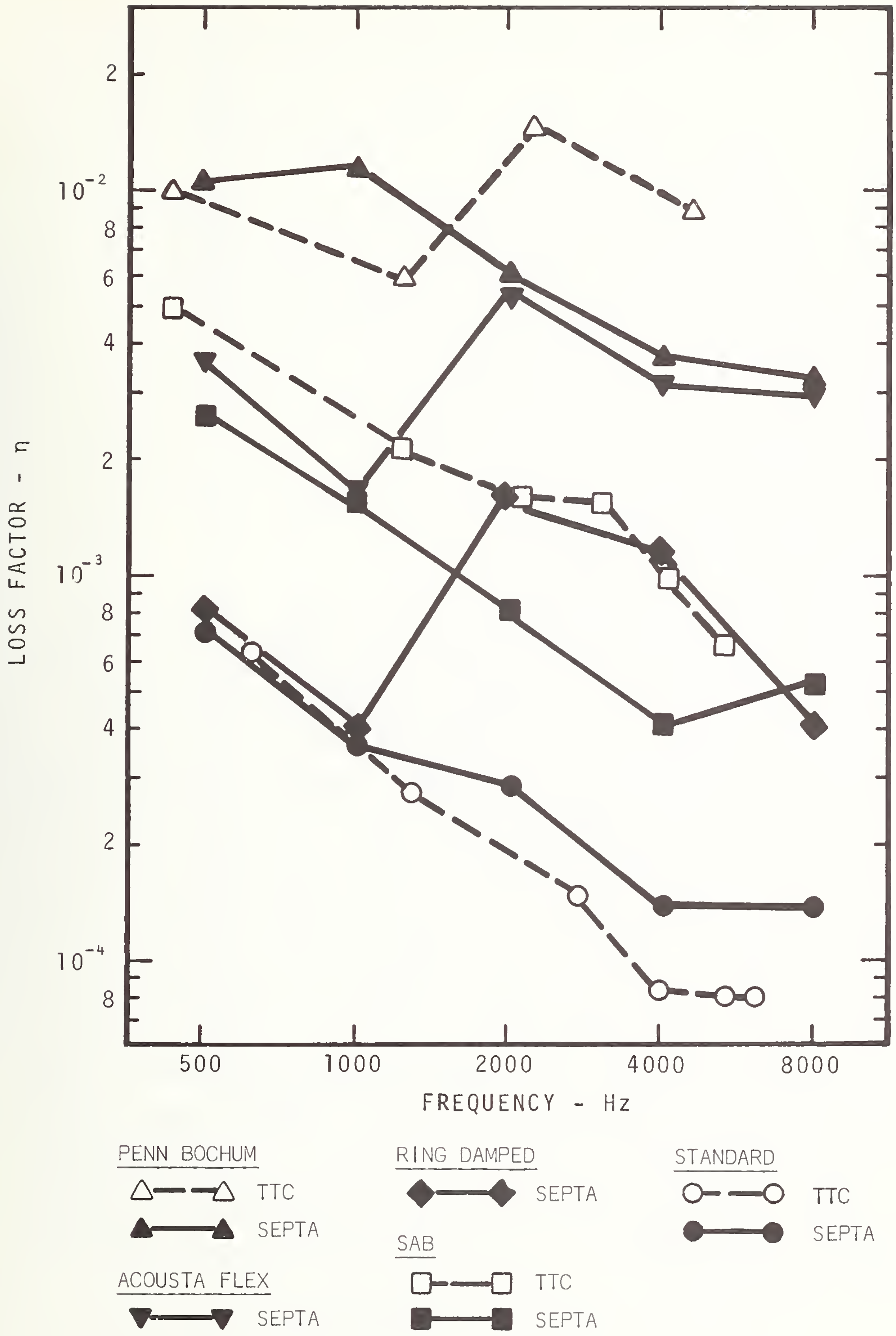


FIGURE 6-3. AVERAGE LOSS FACTORS FOR TEST WHEELS

The results indicated in Figure 6-3 show that:

- All three types of resilient wheels have much higher damping than the standard wheels.
- The ring-dampers do not provide damping below about 1400 Hz. Above about 1400 Hz the ring-dampers provide damping equal to or greater than the SAB wheels.
- The Penn Bochum wheels are the most highly damped of the wheels tested.
- The SAB wheels provide considerably less damping than the other two types of resilient wheels.

Figure 6-4 illustrates the results for the four tests with ring-damped wheels. In the 500 Hz and 1000 Hz octaves, the wheels have the same or only slighlty greater damping than the undamped steel wheels. Above 1000 Hz the ring-damped wheels have 5 to 10 times the damping of the standard wheels. There is a considerable amount of loss factor variation with the four ring-damped wheels. It appears that small variations in the position of the damping ring in the groove can have a significant effect on the damping loss factors. This is indicated by the differences between the Ring-Damped #1 and Ring-Damped #2 Tests. These tests were performed on the same wheel with the ring removed and reinstalled between tests. The loss factors in the 4000 Hz and the 8000 Hz octave bands were more than three times greater for Ring-Damped #2 than for Ring-Damped #1. The difference can only be due to minor differences in the position and/or seating of the damping ring since all other test conditions were identical.

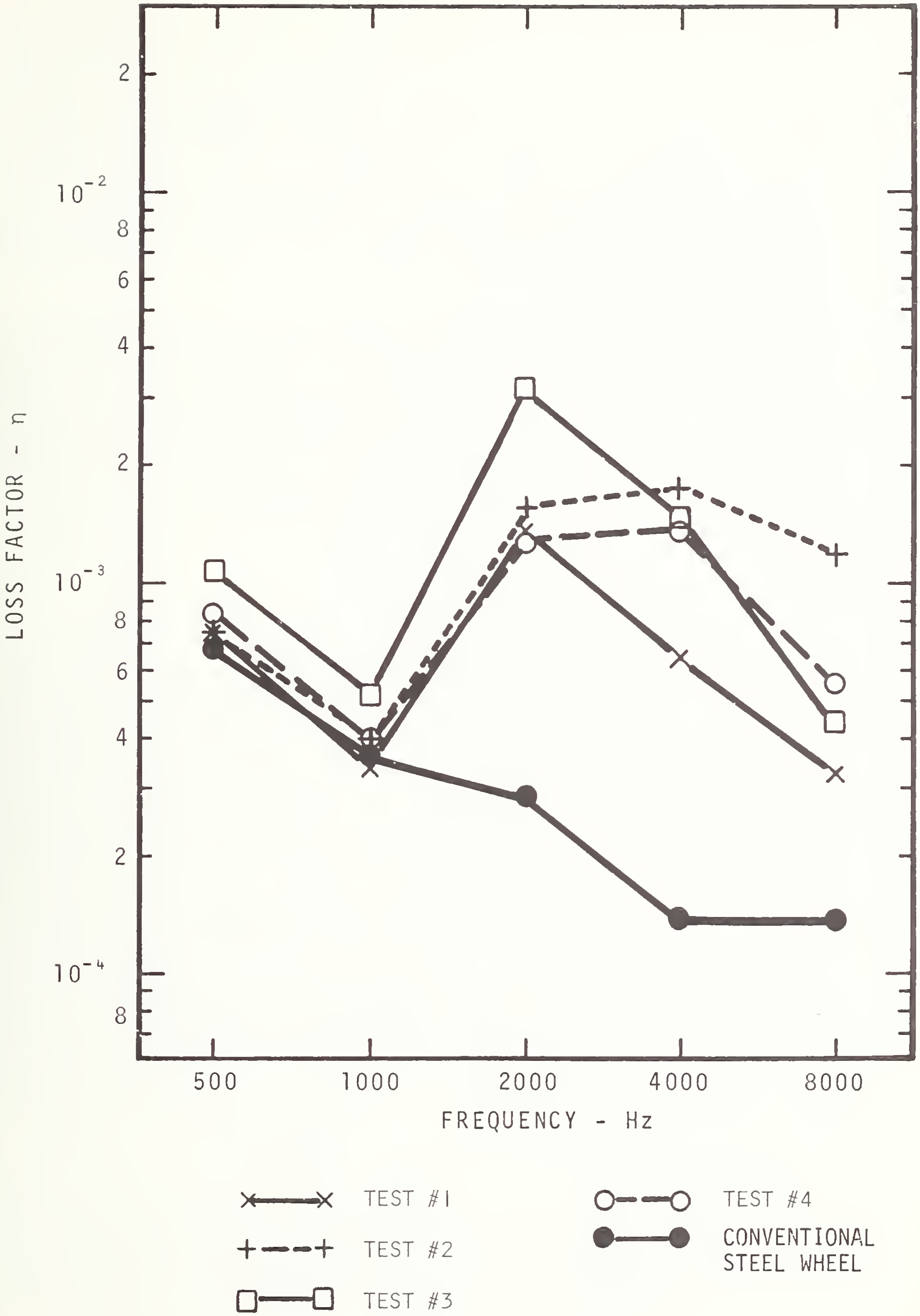


FIGURE 6-4. LOSS FACTORS FOR THE RING-DAMPED WHEELS

Another factor that is likely to have an influence on the damping provided by the rings is the rust layer that develops on the ring and on the wheel. Wheel #3 had been in revenue service for approximately two weeks before the test and had developed a thin layer of rust. The rust may have resulted in an increase in the damping in the 2000 Hz octave although there is no indication of the rust affecting damping at other frequencies.

One particularly interesting result that occurred with the ring-damped wheels was a strong beating characteristic in the 500 and 1000 Hz octave bands. An example of the beating is shown in Figure 6-2d. This beating characteristic occurred with all of the ring-damped wheel tests except wheel #3 that had a layer of rust on the wheel and on the ring.

Figure 6-5 presents the loss factor results for each of the tests with resilient wheels. The Penn Bochum and the SAB test wheels show relatively small variations for the two test wheels. However, the first Acousta Flex test wheel has substantially the same damping as the two Penn Bochum wheels over the entire frequency spectrum, while the second Acousta Flex wheel has an order of magnitude lower damping in the 500 Hz and 1000 Hz octave bands. The data from these tests are insufficient to positively identify the reason for differences between the two Acousta Flex wheels. However, a reasonable explanation is that the elastomer wheel bond for wheel #2 was inferior to the bond for wheel #1 allowing the rim of wheel #2 to vibrate freely at frequencies below about 1500 Hz.

6.3 SUMMARY

The tests of the vibration decay of the wheels show

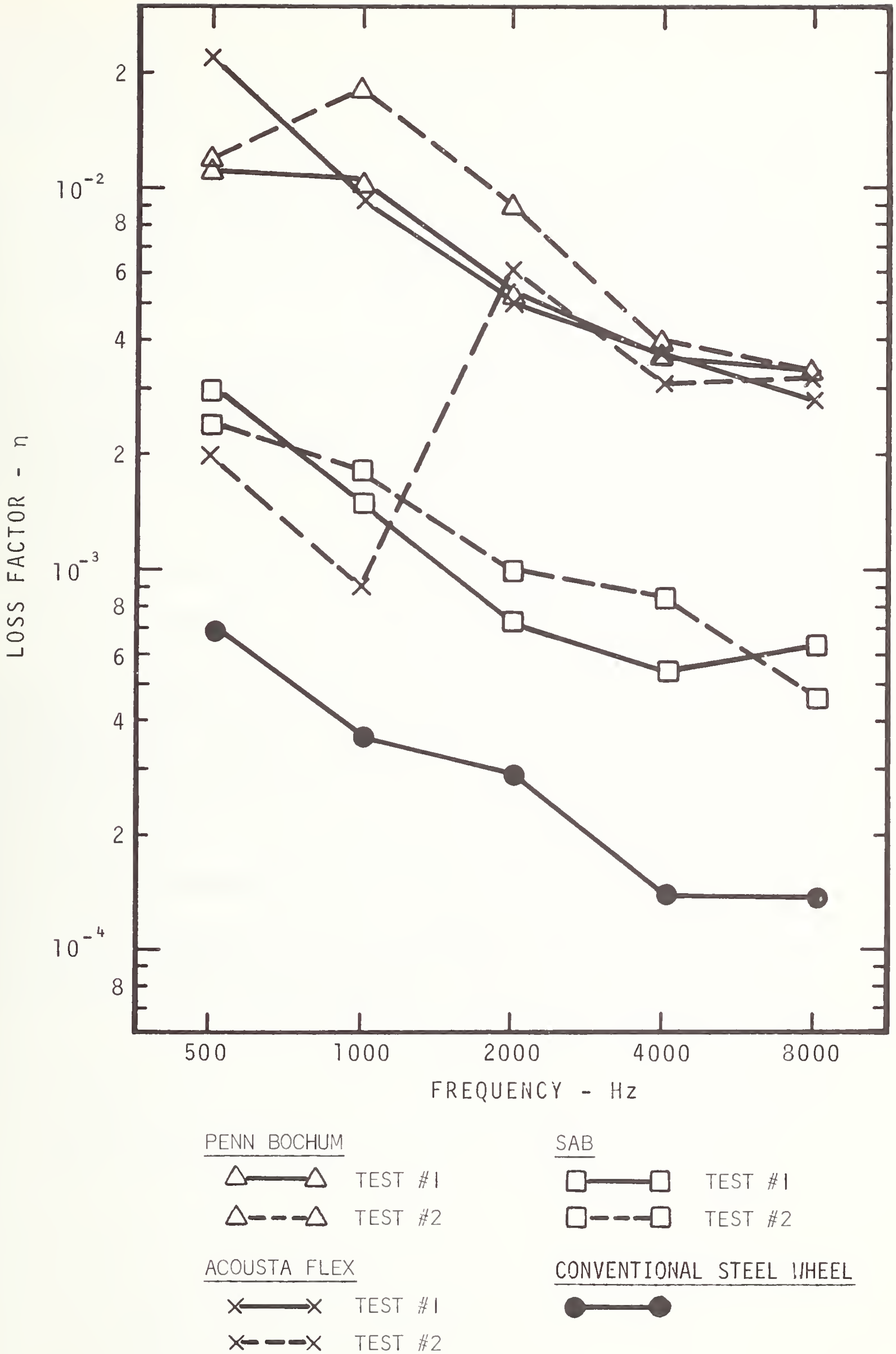


FIGURE 6-5. LOSS FACTORS FOR THE RESILIENT WHEELS

that all of the resilient wheels have much higher damping than the conventional solid steel wheels. The Penn Bochum wheels have the highest damping and the SAB wheels have the lowest damping of the resilient wheels.

The tests with the ring-damped wheels show that below about 1400 Hz the ring-dampers have little effect and above 1400 Hz the ring-dampers result in the same or higher damping than the SAB wheels.

The loss factor results correspond very well with the tests of wheel squeal at the 69th Street turnaround. Most of the squeal at SEPTA occurs at frequencies above 2000 Hz, and all of the resilient wheels and the ring-damped wheels were very effective at reducing this squeal. The Penn Bochum wheels virtually eliminated squeal, the Acousta Flex wheels had only limited amount of intermittent squeal above 2000 Hz, and the SAB wheels have much lower squeal levels than the standard solid steel wheels but did exhibit intermittent squeal over a fairly wide frequency range. As discussed in Section 4, the tests with the ring-damped wheels in Phase VI indicate that the ring-dampers lose effectiveness if they are frozen in the grooves by corrosion or material entrainment in the gap between the ring and groove. Unfortunately it was not possible to measure damping loss factors on one of the wheels with the ring frozen in the grooves. The test results presented in this section indicate that the loss of damping effectiveness could be evaluated with vibration decay measurements.

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5. S. Peters, "The Prediction of Railway Noise Profiles," Journal of Sound and Vibration, 32(1), 87-89; 1974.

6. Leo L. Beranek, Noise and Vibration Control, Chapter 14, McGraw-Hill Book Company, 1971.

7. N. Perfect, "Vibration Testing of Damped and Undamped Steel Wheels, "Testing and Instrumentation Laboratory Report No. 76-TIL-4, Ontario Ministry of Transportation and Communication, February 1976.

APPENDIX A

TABULATION OF A-WEIGHTED SOUND LEVEL DATA
FOR TEST PHASES IV, V, VI AND VII*

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*Notch filter used to remove tonal noise from traction motor fans for all tests on tangent track.

CURVE TEST TRACK - TURN						
Train	Control Track			Test Track		
	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE IV						
Worn Stnd.	18	94.8	78.1	19	99	84
	21	99.5	78.8	21	103	81.4
	23	99.8	76.6	24	98.8	78.1
	20	100.8	77.4	23	99.5	79.2
New Stnd.	19	95.5	82	22	94	76.4
	20	88.8	76	24	100.2	84.2
	20	97	78.2	18	95.2	81.5
	20	97.5	76.1	20	101	87.5
	20	96.5	76.2	20	100.2	79.1
	20	94.2	76	20	102.2	80.5
	20	95.5	80.2	20	99	79.8
Single Grooved - Rings installed (Cars 607/644)	16	76.5	71.4	22	93	78
	20	77.8	71.9	20	79.2	75.2
	18	77.8	73.4	22	84.5	74.9
	20	79.2	73.5	20	78.0	72.2
Single Grooved - w/o Rings - (Cars 607/644)	21	91.8	75.2	28	96	81.8
	15	85.8	75.1	25	100.2	79.8
	21	92.2	74.9	32	93.5	81.5
	20	87	73	22	--	82.1
PHASE V						
Worn Stnd.	21	98	76.1	22	95.2	77.4
	20	88.8	77.6	22	90.0	75.4
	19	98.2	79.5	22	90.8	77.5
	20	90.0	76.8	20	90.2	73.4

CURVE TEST TRACK - TURN [CONTINUED]						
Train	Control Track			Test Track		
	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE V [cont'd]						
New Stnd.	22	94.5	81.2	18	89.8	74.9
	18	95.5	85.9	22	98.2	79.6
	22	91.2	85	24	87.5	79.9
	20	76.8*	71.8*	22	76.2*	69.9*
Single Grooved - Rings installed (Cars 607/644)	18	83.2	74	22	76.2	72.5
	20	79.0	74.9	22	76.5	72.1
	22	79.5	76	24	75.2	72.8
	18	77.2	72.9	22	75.5	72.9
	22	--	--	22	--	--
Single Grooved - w/o Rings - (Cars 607/644)	20	85.2	75.2	24	86	73.9
	20	85.5	74.4	25	86.5	75.8
	20	85.5	73.9	26	85.8	75.5
	20	87.8	74.2	23	90.2	75.2
PHASE VI						
Worn Stnd.	20	90.2	74.1	22	88.8	75.8
	18	92.0	72.8	20	87	75.2
	18	91.2	73.5	22	89.2	75.5
	18	91.2	74.4	21	85.5	75.9
New Stnd.	20	--	75.1	22	--	75.8
	20	--	74.4	20	--	77.5
	20	90	--	20	91.5	--
	20	91.2	--	29	92	
	20	87	--	20	85.2	--
	20	95	--	20	95.8	--

* track wet

CURVE TEST TRACK - TURN [CONTINUED]						
Train	Control Track			Test Track		
	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE VI [cont'd]						
Single Grooved - Rings installed (Cars 607/644)	21	80.8	73	23	78.8	75.1
	20	79.8	72	22	77.2	73.8
	22	81.2	72.5	23	78.2	74.5
	22	81.2	73.1	22	77.0	74.4
Single Grooved - w/o Rings - (Cars 607/644)	18	87	75.8	20	84	74.2
	20	89	76	22	84.5	74.8
	22	92.5	77.4	22	86.5	75.2
	23	93.5	77.2	22	87.0	75.2
PHASE VII						
Double Grooved - Rings both sides (Car 606)	18	76	--	22	74.8	--
	19	76	--	22	76.2	--
	18	75.8	--	22	76.5	--
	18	75.5	--	22	76.8	--
	18	76.5	--	22	76	--
	18	76.8	--	22	76.5	--
Double Grooved - Rings on inside (Car 606)	19	76.5	--	23	76	--
	19	76.5	--	23	78.5	--
	19	76.8	--	23	78	--
	19	75.8	--	23	78	
	20	76.5	--	23	79	
	19	76.8	--	23	78.2	--

CURVE TEST TRACK - TURN [CONTINUED]						
Train	Control Track			Test Track		
	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE VII [cont'd]						
Double Grooved - Rings on field side (Car 606)	19	75.2	--	22	79	--
	19	75.8	--	22	75.8	--
	19	75.8	--	22	75.2	--
	19	76.5	--	22	74.5	--
	19	76.2	--	22	77.2	--
	19	76.5	--	22	75	--
Double Grooved - w/o Rings - (Car 606)	19	75.5	--	22	79.8	--
	19	77.2	--	22	75.8	--
	19	78.8	--	22	82.5	--
	18	79.5	--	21	81.8	--
	21	81.2	--	21	80	
	21	78.5	--	21	82.8	--
	19	77.2	--	--	--	--
Single Grooved - Rings rusted in place (Cars 607/ 644)	20	78.8	--	22	80.8	--
	20	85.5	--	22	81.5	--
	20	86	--	22	80.8	--
	20	86.2	--	22	81.5	--
	18	86	--	18	77.8	--
	20	86.8	--	22	80	--
Single Grooved - Freshly installed rings - (Cars 607/ 644)	18	80	--	21	77.2	--
	19	76.8	--	21	75.5	--
	19	76.5	--	22	76.8	--
	19	76.5	--	22	76.8	--
	18	77	--	22	75	--
	18	77	--	21	76.8	--

Train	CURVE TEST TRACK - TURN [CONTINUED]					
	Control Track			Test Track		
	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE VII [cont'd]						
Single Grooved - w/o Rings (Cars 607/644)	22	83.2	--	22	83.5	--
	22	83.8	--	22	85.5	--
	22	82.5	--	22	82.8	--
	20	86.8	--	20	83.5	--
	19	90	--	19	82.5	--
	22	86.8	--	22	86.2	--
	18	91.5	--	20	87.8	--
Single Grooved - Freshly installed rings (Car 607)	18	79.5	--	21	75.5	--
	18	79.5	--	22	78.5	--
	17	76	--	21	76.2	--
	18	81.2	--	22	78	--
	18	79	--	22	77.5	--
	19	81.8	--	23	77	--
Single Grooved - w/o Rings (Car 607)	18	95	--	21	81.8	--
	22	89.8	--	18	81.2	--
	18	89.5	--	22	82.5	--
	17	95.5	--	19	80.5	--
	19	93.5	--	20	82	--
	18	96.2	--	21	83.2	--

SUMMARY OF TEST RESULTS - A-WEIGHTED SOUND LEVEL

TANGENT WELDED TRACK - TW							
Train	Direction	Control Track			Test Track		
		Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE IV							
Worn Stnd. [cars 613/623]	W	45	82.5	77	43	81.5	76.5
	W	63	87.2	81	61	87	81
	W	62	86.8	80.5	59	86.5	80.5
	W	62	86.5	80.2	58	86.2	80.4
	W	68	88.5	81.8	72	89	82.9
New Stnd. [cars 755/756]	W	48	83	75.6	52	--	77.8
	W	60	86.8	79.8*	62	-	81*
	W	84	91.5	83.5*	85	-	84*
	W	84	91.5	84*	84	-	84*
	W	46	82.5	75.1	50	84	76.5
	W	81	-	84.8	81	-	85.5
	W	83	91.5	84.9	85	91.5	85.6
	W	64	86	80.1	65	86.8	81
	W	69	89.2	82	69	88.2	80.4
Single Grooved-rings installed [cars 607/644]	W	40	78.5	73.2	42	-	74.5
	W	60	83	77.6	62	-	80
	W	64	84.5	78.5	71	-	80.6
Single Grooved-without rings [cars 607/644]	W	42	78.5	72.6	41	78	72.1
	W	60	83.2	77.2	63	84.2	78.2
	W	67	86	78.1	65	84.2	78.8
	W	68	-	78.6	70	-	79.1

*No data over truck, adjustment of
1 dB added to car-center data.

TANGENT WELDED TRACK - TW (Continued)							
Train	Direction	Control Track			Test Track		
		Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE V							
Worn Stnd. [613/623]	W	42	80	74.1	44	81	74.9
	W	59	85.5	79.5	59	85.8	80.5
	W	70	89.2	82.1	73	89.5	83.2
	W	63	86.8	80.5	62	85.8	80.8
New Stnd. [cars 755/756]	W	44	81.5	74.5	42	78.8	74.5
	W	63	86	78.2	59	84	77.9
	W	62	-	79.2	58	84.8	78
	W	81	90.8	82.4	82	91	82.8
	W	64	86	78.6	64	86	-
Single Grooved-rings installed [cars 607/644]	W	44	78.5	74.9	44	-	75.1
	W	58	82.8	77.6	58	81.8	79
	W	61	83	78.8	60	81.8	79.1
	W	65	83.5	79.9	67	83.5	80.6
Single Grooved-without rings [607/644]	W	44	81	75	42	77.8	74.9
	W	61	83	77.9	62	82.5	79.2
	W	62	83	79.8	62	82.5	81.2
	W	65	85	80.4	67	83.5	80.9
PHASE VI							
Worn Stnd. [cars 613/623]	W	42	85	78.9	42	80.2	77.8
	W	62	89.2	81.8	62	85.5	82
	W	62	89.2	82.1	61	85.5	81.9
	W	80	93.5	85.9	85	91	86.1

TANGENT WELDED TRACK - TW [CONTINUED]							
Train	Direction	Control Track			Test Track		
		Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE VI [cont'd]							
New Stnd. [cars 613/623]	W	40	84.8	78	43	82.8	78.4
	W	58	90.2	82.1	57	86.2	82.4
	W	58	89.2	82.4	63	88	83.8
	W	70	91.8	85.8	-	-	-
	W	80	95.2	87	80	91.2	87
Single Grooved-rings installed [cars 607/644]	W	43	83.2	76.4	46	80.5	77.5
	W	63	88	80.8	64	84	81.4
	W	64	88.2	81.2	64	84.5	81
	W	65	88.2	81.2	68	85.8	82.5
Single Grooved-without rings [cars 607/644]	W	42	82.2	77.5	40	77.5	76.8
	W	62	87.5	82.8	59	83.5	81.5
	W	62	87.8	82.4	58	83	81.6
	W	62	88.2	82	66	84.2	82.9

SUMMARY OF TEST RESULTS - A-WEIGHTED SOUND LEVEL

TANGENT JOINTED TRACK - TJ										
Train	Direction	Control Track			Test Track A			Test Track B		
		Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE IV										
Worn Stnd. [cars 613/623]	W	40	-	78.5	40	-	76.8	40	-	77.2
	W	63	-	83.5	63	-	82.1	62	-	82.2
	W	61	88.2	82.6	63	87	81.8	62	87.5	82.2
	W	60	89.5	82.9	60	87	81.1	59	86.7	81.6
	W	60	89	83.8	58	-	81.5	60	-	82.9
New Stnd. [cars 755/756]	W	46	84.8	77.6	46	83.2	76.1	47	83.8	77.1
	W	58	-	81.8*	63	-	80.8*	62	-	81.5*
	W	83	93.5	84.8*	83	90.2	84*	83	91.5	84*
	W	86	93.8	85.8*	86	92.8	84.2*	86	92.5	84.2*
	W	50	87.2	79.9	50	86.8	78.8	52	85	80.2
	W	82	92.5	86.2	80	90	84.9	78	88.5	84.2
	W	83	92	86	82	92	84.2	80	87.8	84.2
	W	74	90.5	85	72	90.5	82	68	-	81.9
	W	83	91	85	82	92.5	83.2	80	88.8	83.8
Single Grooved-rings installed [cars 607/644]	W	40	83.8	78.2	40	82	78.8	40	82.2	77.1
	W	56	87	82.4	54	-	80.4	62	-	82
	W	67	87	83.2	65	87.5	81.2	66	87.2	82

*No data over truck, adjustment of 1 dB added to car-center data - based on average results with both over truck and car-center data.

TANGENT JOINTED TRACK - TJ [CONTINUED]

Train	Direction	Control Track			Test Track A			Test Track B		
		Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE IV [cont'd]										
Single Grooved-without rings [cars 607/644]	W	45	84	79.5	41	80	75.1	41	81.0	74.4
	W	64	88	81.6	-	-	-	58	85.2	79.5
	W	69	90.2	84	66	87	80.4	60	85.8	80
	W	64	87	82.4	65	86.2	80.1	66	85.8	80.9
PHASE V										
Worn Stnd. [cars 613/623]	W	40	87.2	78.9	38	82	75.5	40	83	76.9
	W	58	92	82.8	58	87.2	80.5	57	86.5	81.2
	W	69	95	85.5	70	90.5	82.9	70	90	83.5
	W	59	92.5	83.4	58	87.8	81	57	87	80.9
New Stnd. [cars 755/756]	W	40	86	76.8	38	82.2	74	42	83	76
	W	58	90.5	80.6	59	87	78.8	60	86	79.6
	W	42	87	77	42	82.5	74.9	42	81.8	75.6
	W	83	96.2	84.9	81	91.2	82.9	80	90.8	83.1
	W	60	92.5	81.8	62	87.5	79.5	60	87	79.8

TANGENT JOINTED TRACK - TJ [CONTINUED]

Train	Direction	Control Track			Test Track A			Test Track B		
		Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE V [cont'd]										
Single Grooved-rings installed [cars 607/644]	W	40	84.5	78.9	40	80.5	76.1	42	80.5	76.7
	W	58	88.5	83.2	60	86	81	60	--	81.1
	W	60	89	83.4	61	86	80.5	57	84.8	80
	W	62	89.2	83.8	64	86	81.4	66	87.5	81.1
Single Grooved-without rings [cars 607/644]	W	43	84.8	79.9	44	82	77.9	44	82.8	77.5
	W	60	89.5	83.8	58	85	80.6	61	86.5	81.4
	W	64	90.5	84.9	62	85.5	80.5	59	86	80.1
	W	63	89.5	84.2	64	86	82.1	65	88	81.6
PHASE VI										
Worn Stnd. [cars 613/623]	W	46	--	80.4	42	--	77.6	40	--	78.9
	W	62	--	85.2	61	--	83.2	60	--	82.5
	W	63	--	84.2	62	--	82.9	61	--	82.8
	W	78	--	87.2	78	--	86.4	76	--	86.4
New Stnd. [cars 755/756]	W	42	--	79.6	46	--	80	40	--	79.8
	W	58	--	85	62	--	83.6	59	--	83.9

TANGENT JOINTED TRACK - TJ [CONTINUED]										
Train	Direction	Control Track			Test Track A			Test Track B		
		Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA	Speed km/hr	Wayside dBA	Interior dBA
PHASE VI [cont'd]										
New Stnd. [cars 755/756]	W	62	--	85.4	60	--	83	60	--	83.6
	W	68	--	86.8	68	--	84.6	68	--	85.2
	W	72	--	87.5	73	--	85.6	73	--	86.2
Single Grooved-rings installed [cars 607/644]	W	38	--	78.6	40	--	76.4	40	--	77
	W	63	--	84.1	65	--	82.2	66	--	83.8
	W	63	--	84.2	60	--	81.5	63	--	82.5
	W	62	--	84.8	63	--	82.1	65	--	83.4
Single Grooved-without rings [cars 607/644]	W	43	--	81.1	40	--	77.1	40	--	--
	W	58	--	85.2	58	--	82.1	59	--	83.2
	W	58	--	84.9	58	--	82.2	60	--	83.4
	W	52	--	83.8	58	--	82.5	64	--	84.1

SUMMARY OF SUBWAY TEST RESULTS, CAR INTERIOR-
A-WEIGHTED SOUND LEVEL

SUBWAY TEST TRACKS					
Train	Direction	Welded		Jointed	
		Speed	dBA	Speed	dBA
PHASE IB					
Worn Stnd. [cars 613/623]	E	47	78.2	45	79.9
	W	42	76.8	41	79.2
	E	62	83.2	56	83.6
	W	62	82.6	61	84.6
	E	63	83.5	66	86.4
	W	78	86.8	76	87.8
	E	70	85.2	76	88.1
New Stnd. [cars 755/756]	E	47	78.6	44	78.2
	W	42	74	42	78.4
	E	65	81.9	61	82.5
	W	56	78.8	59	82.9
	E	71	82.5	77	86.1
	W	79	83	76	84.5
	E	59	80.2	58	81
PHASE IIA					
Acousta Flex	E	44	77.8	49	80.5
	W	56	80.9	64	84.8
	E	40	78.2	41	79.4
	W	54	81.4	62	85.5
	E	40	77.9	50	81.5
	W	52	80.6	48	81.5
Penn Bochum	W	64	82	64	83.2
	E	56	80	64	83.1
	W	65	81.5	65	83.6
	E	44	77.8	41	81.5

SUBWAY TEST TRACKS (Continued)					
Train	Direction	Welded		Jointed	
		Speed	dBA	Speed	dBA
PHASE IIA [cont'd]					
Penn Bochum	W	43	77	43.	80
	E	54	81.6	57	83.8
	W	41	76.4	42	79.2
	W	66	84.2	--	--
	E	53	81	--	--
	W	46	78.4	--	--
	E	38	77.2	--	--
	W	66	84.5	--	--
	E	54	81.6	--	--
SAB	E	59	82	59	82.8
	W	59	80.9	61	85.1
	E	68	83.6	72	86.5
	W	74	85.1	68	86.1
	E	48	78	43	78.9
	W	44	75.5	41	80
	E	45	74.8	--	--
PHASE IIB					
Worn Stnd. [cars 613/623]	E	64	86.9	67	89.2
	W	67	86.8	71	90.1
	E	80	89.8	69	89.1
	W	45	80.2	43	82.1
	E	41	80.1	40	81.4
	W	62	85	57	85.8

SUBWAY TEST TRACKS (Continued)					
Train	Direction	Welded		Jointed	
		Speed	dBA	Speed	dBA
PHASE IIB [cont'd]					
New Stnd. [cars 755/756]	E	59	80.5	55	81.4
	W	60	80.2	61	82.5
	E	69	82.8	76	84.2
	W	78	84.5	70	85.2
	E	47	78.9	39	77
	W	42	76	44	78.1
Acousta Flex	E	59	78.8	57	80.2
	W	56	78	56	80.6
	E	55	78	60	80.9
	W	65	80.9	66	83.8
	E	48	76.8	40	75.1
	W	40	74.6	41	76.8
Penn Bochum	E	51	77.6	58	80.5
	W	58	77.9	60	81
	E	56	78.2	60	81
	W	76	83.5	72	83.5
	E	40	74	40	75.5
	W	42	73.5	41	75.4
SAB	E	61	80.6	61	82
	W	58	79.5	56	82.1
	E	69	82.4	74	85.1
	W	76	83.9	72	85
	E	41	75.1	42	76.6
	W	44	74.5	42	75.9

SUBWAY TEST TRACKS (Continued)					
Train	Direction	Welded		Jointed	
		Speed	dBA	Speed	dBA
PHASE III					
Worn Stnd. [cars 613/623]	E	47	79.8	38	79
	E	60	83.5	58	84.8
	E	68	85.2	74	87.4
	E	40	79.6	40	81.5
	E	55	83.6	61	87.4
Acousta Flex, Penn Bochum	E	46	75	54	81
	E	65	82.5	63	84.9
	E	68	82.6	76	86.2
	E	42	77.6	43	81.2
	E	63	83.9	62	86.2
	E	72	86.1	77	90.1
PHASE IV					
Worn Stnd. [cars 613/623]	E	45	84	30	--
	E	60	88.1	63	90
	E	69	88.9	76	91.8
	E	63	87.5	60	88
New Stnd. [cars 755/756]	E	42	80.4	41	79.4
	E	63	86.5	60	84.8
	E	60	86.5	51	83
	E	69	86	80	87.8
Single Grooved-rings installed [cars 607/644]	E	47	82.6	36	79.9
	E	62	85	67	87
	E	60	85	57	84.4

SUBWAY TEST TRACKS (Continued)					
Train	Direction	Welded		Jointed	
		Speed	dBA	Speed	dBA
PHASE IV [cont'd]					
Single Grooved-without rings [cars 607/644]	E	45	78.8	46	79.6
	E	60	82.6	46	79.5
	E	64	83	61	83.6
	E	65	83.5	72	85.9
PHASE V					
Worn Stnd. [cars 613/623]	E	41	82.1	41	82
	E	52	85	55	86.6
	E	50	84.4	58	86.6
	E	52	84.8	58	87
New Stnd. [cars 755/756]	E	39	77.5	40	77.5
	E	59	83.9	60	83.6
	E	57	81.6	58	82.2
	E	75	85.6	80	87.1
Single Grooved-rings installed [cars 607/644]	E	43	78	42	78.2
	E	61	83	61	83.1
	E	58	81.2	--	--
	E	64	83.9	62	84.6
Single Grooved-without rings [cars 607/644]	E	41	77	42	--
	E	59	82.8	60	83.6
	E	60	83.4	60	84.6
	E	58	82.6	60	84.5

APPENDIX B

CAR INTERIOR WHEEL SQUEAL SPECTRA FOR TEST PHASES IB, IC AND IIA

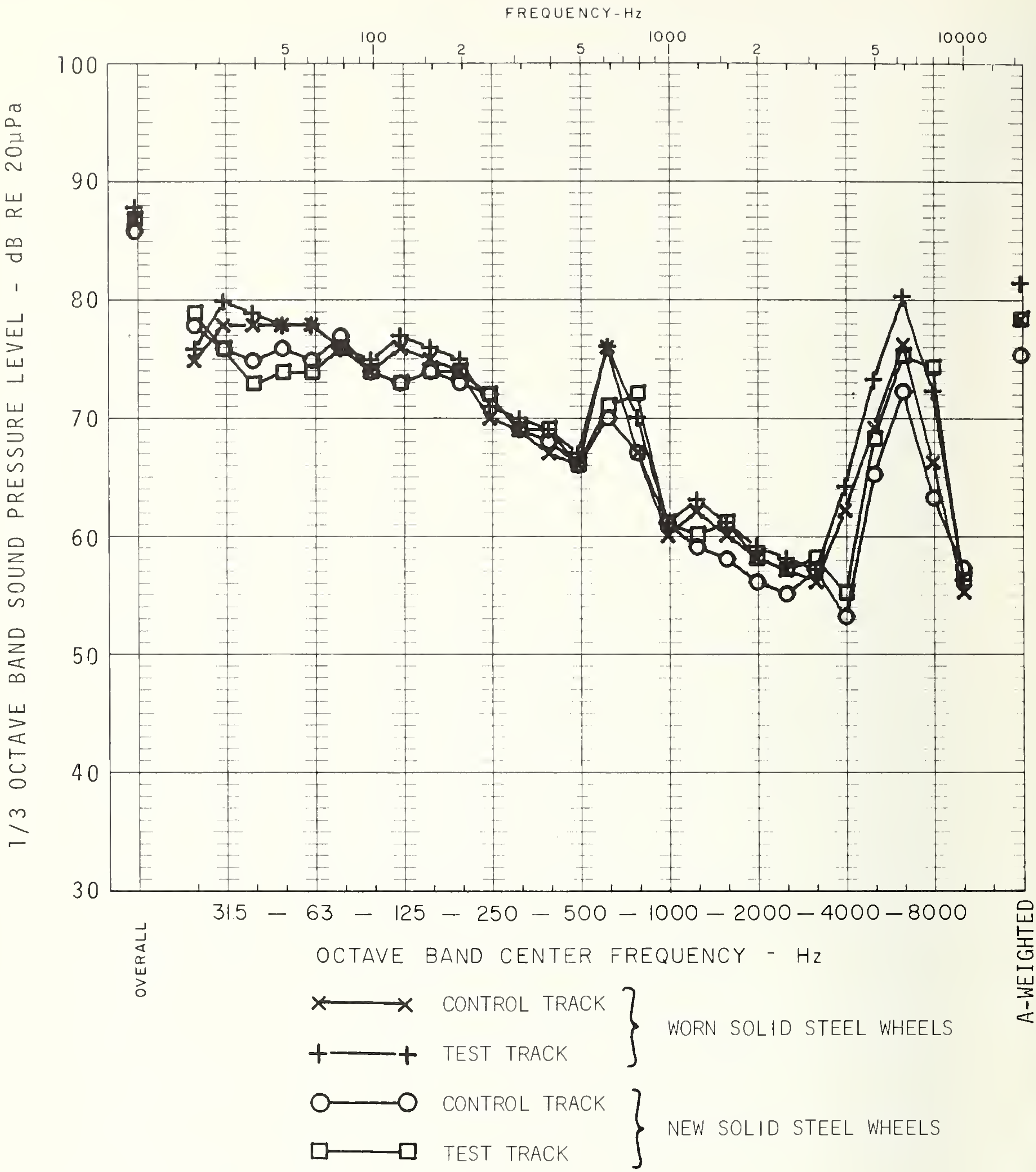

FIGURE B-1. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IB; AUGUST 18, 1976
ENERGY AVERAGE OF ALL TESTS
CAR INTERIOR NOISE - OVER TRUCK

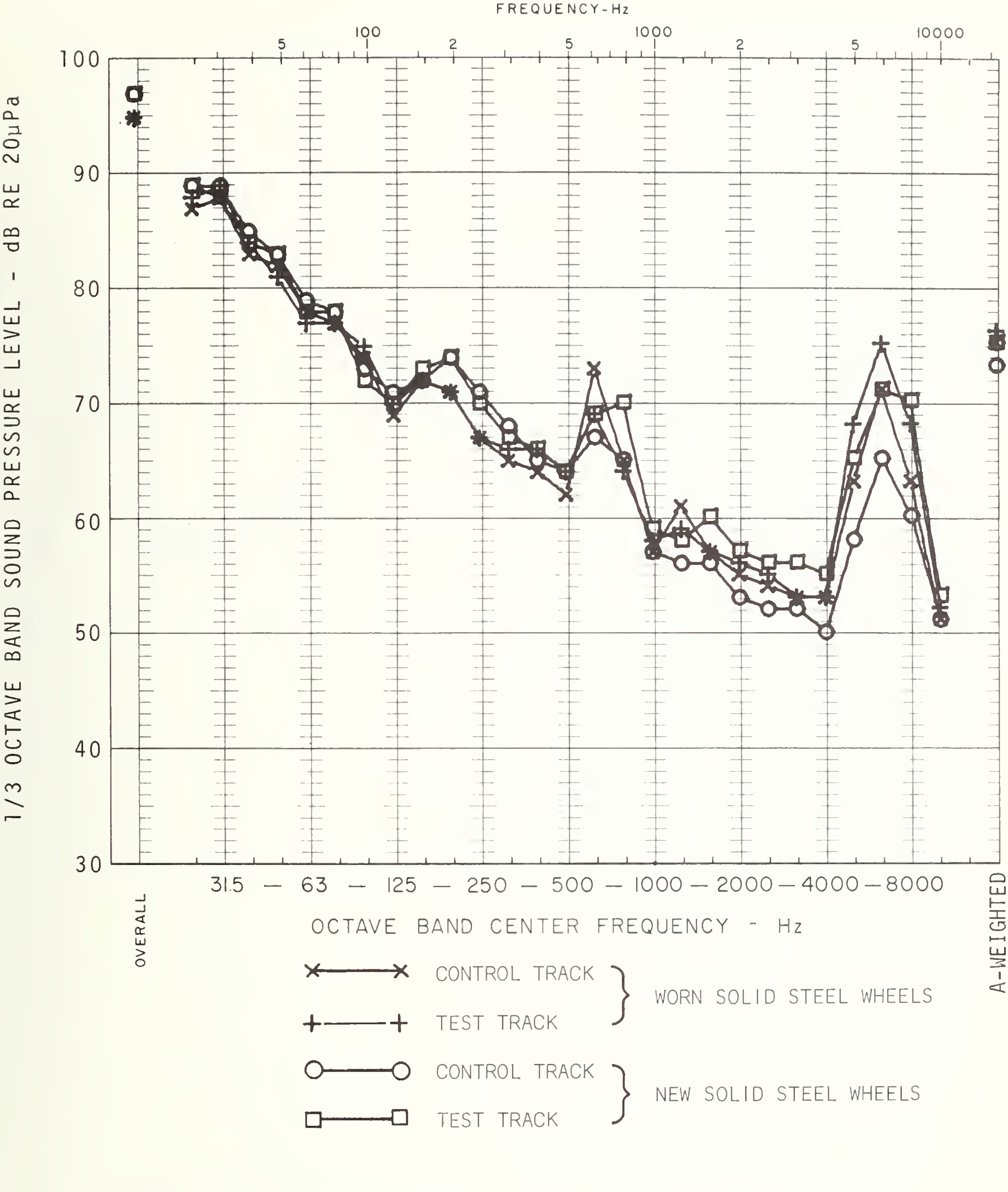

FIGURE B-2. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IB; AUGUST 18, 1976
ENERGY AVERAGE OF ALL TESTS
CAR INTERIOR NOISE - CAR CENTER

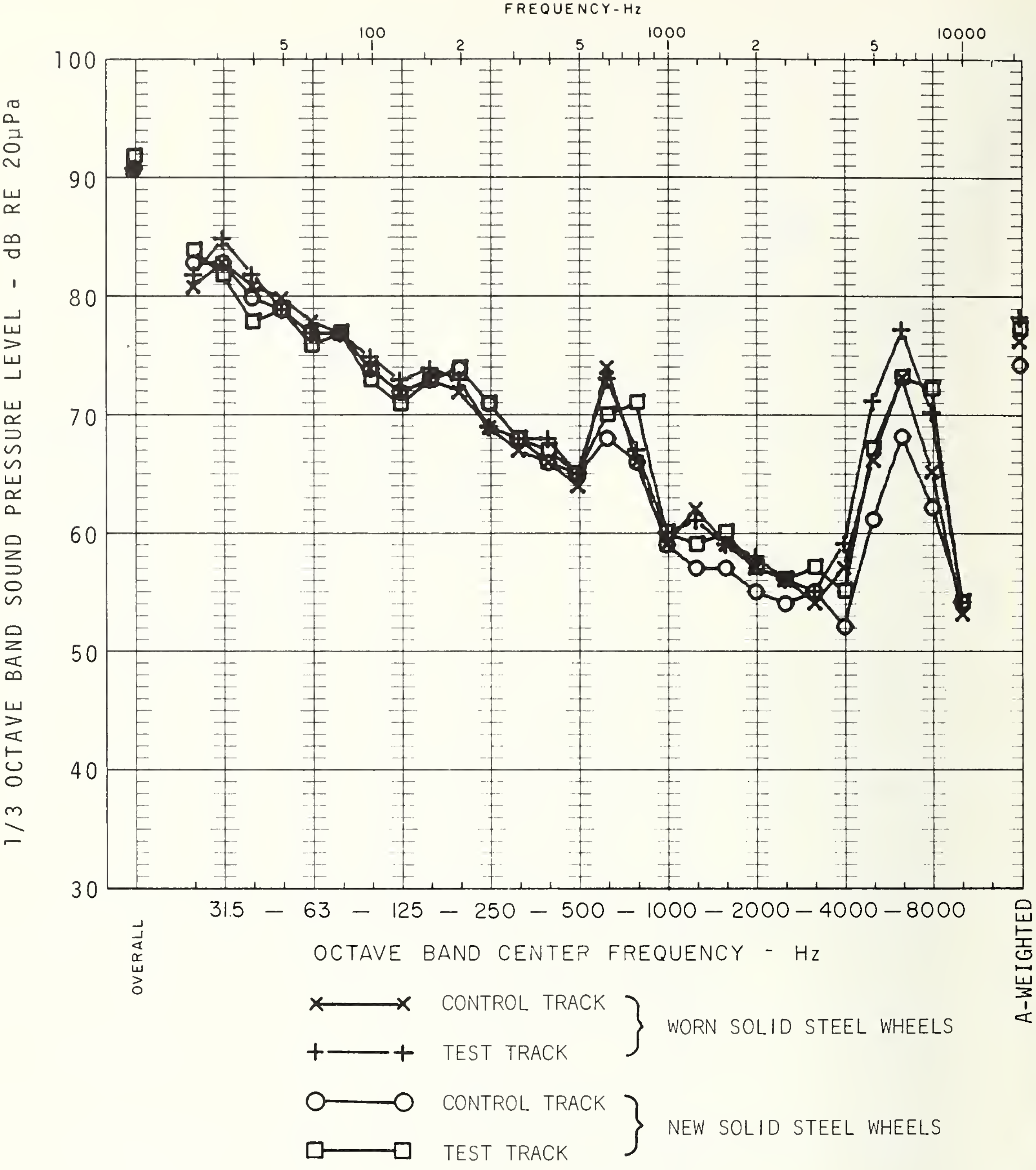

FIGURE B-3. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IB; AUGUST 18, 1976
AVERAGE OF ALL TESTS [ENERGY] AND BOTH MEASUREMENT LOCATIONS [LINEAR] - CAR INTERIOR NOISE

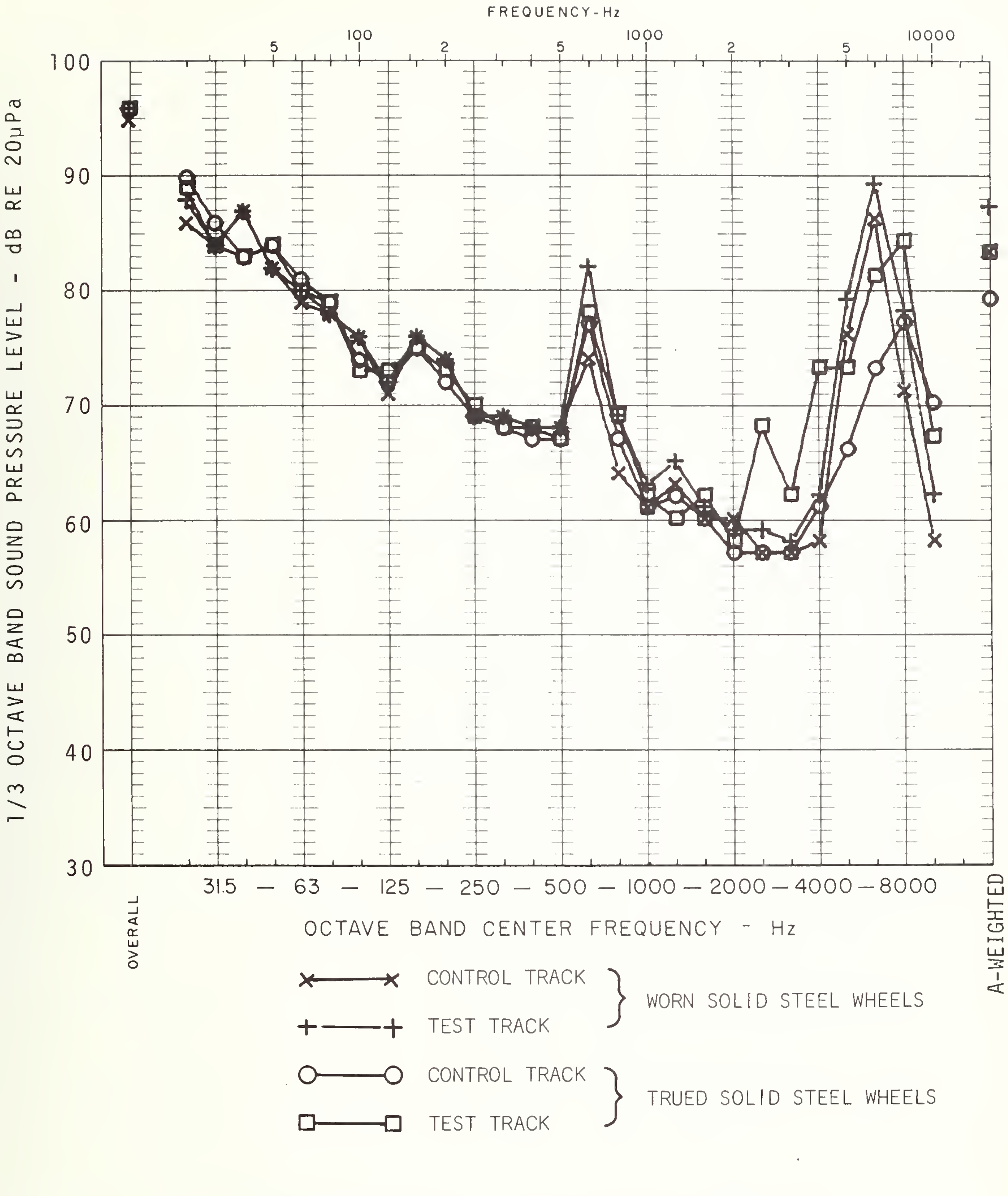

FIGURE B-4. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IC; SEPTEMBER 1, 1976
ENERGY AVERAGE OF ALL TESTS
CAR INTERIOR NOISE - OVER TRUCK

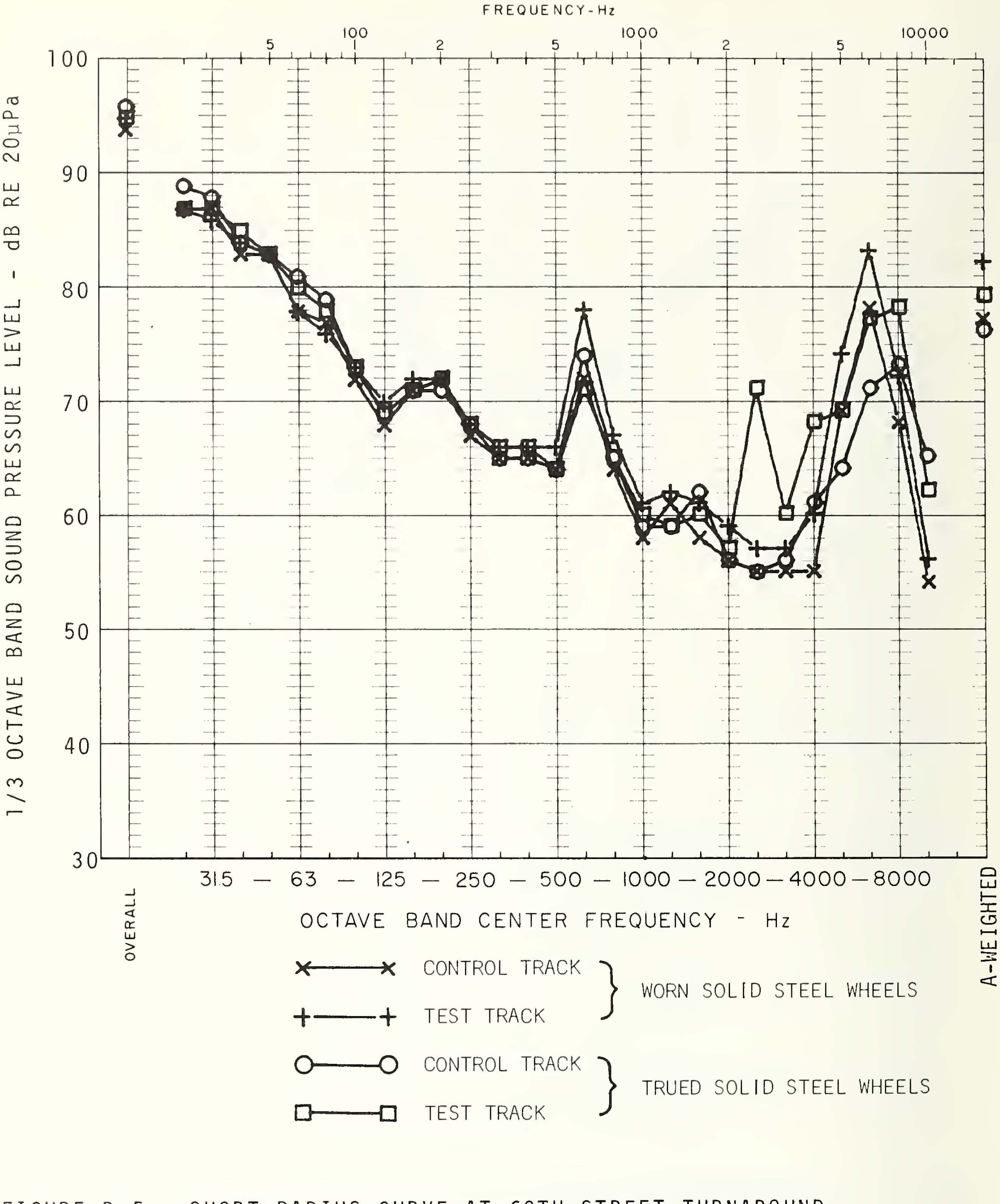

FIGURE B-5. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IC; SEPTEMBER 1, 1976
ENERGY AVERAGE OF ALL TESTS
CAR INTERIOR NOISE - CAR CENTER

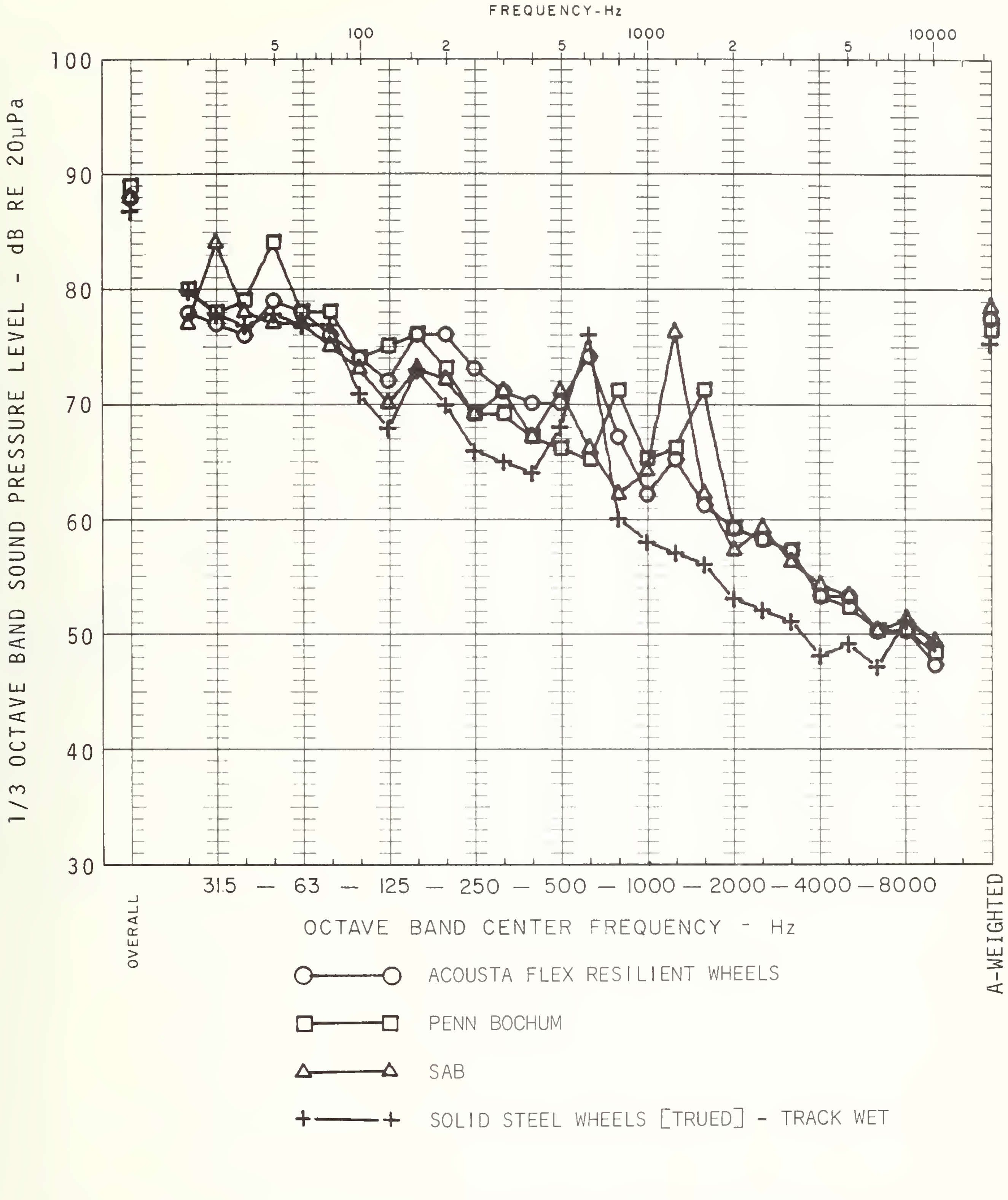

FIGURE B-6. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IIA; OCTOBER 3, 1976
ENERGY AVERAGE OF ALL TESTS ON CONTROL TRACK SEGMENT
CAR INTERIOR NOISE - OVER TRUCK

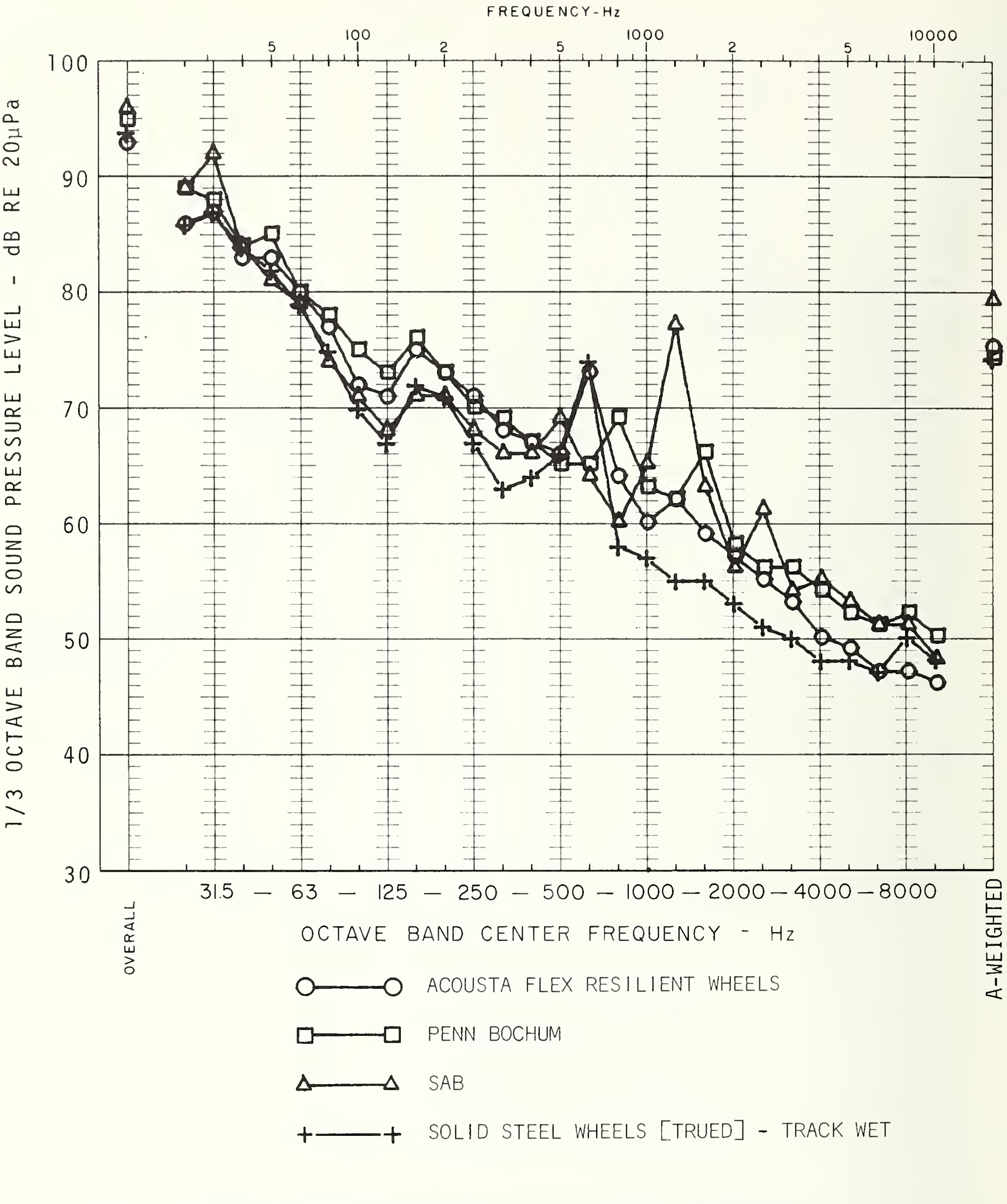

FIGURE B-7. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IIA; OCTOBER 3, 1976
ENERGY AVERAGE OF ALL TESTS ON CONTROL TRACK SEGMENT
CAR INTERIOR NOISE - CAR CENTER

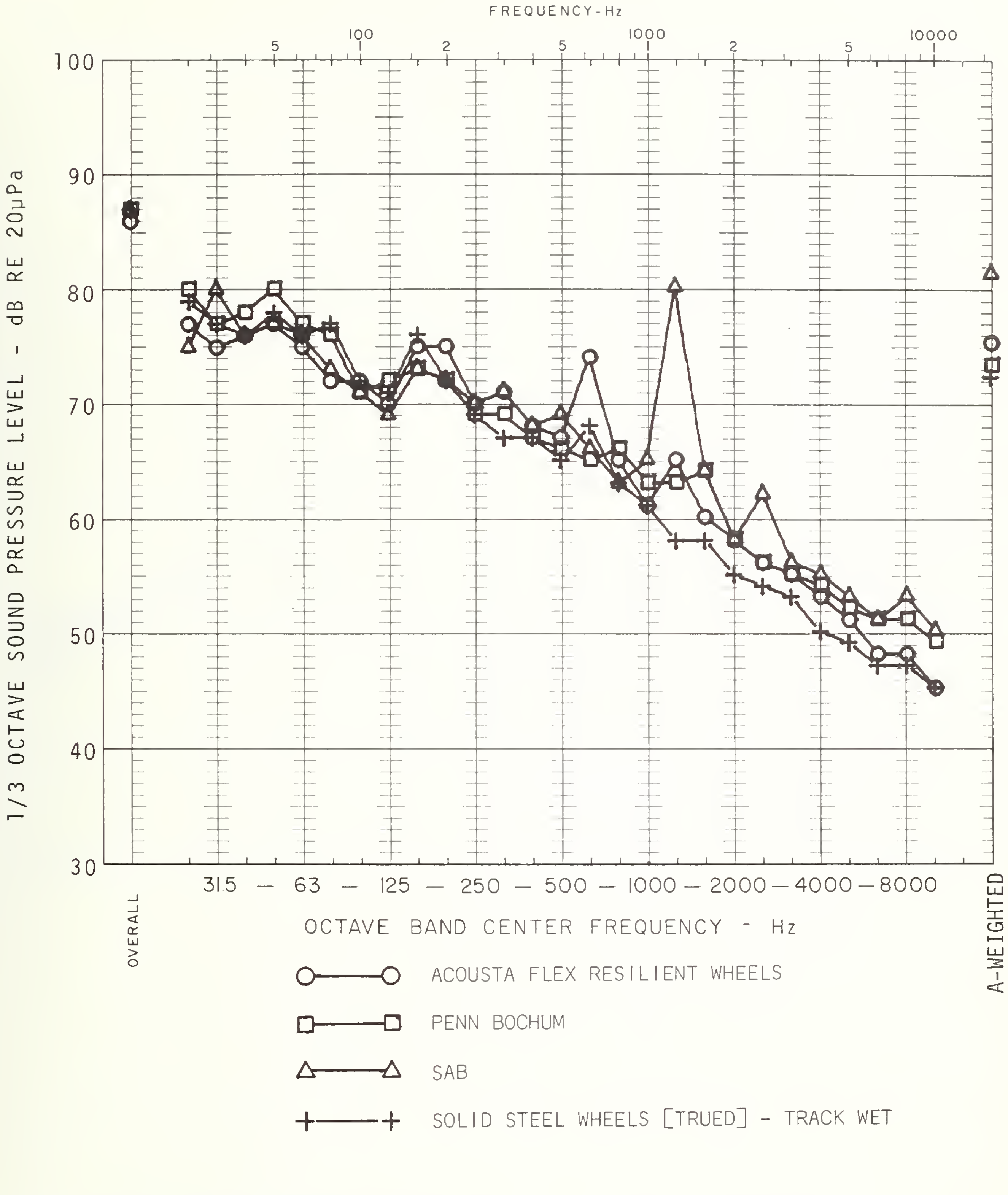

FIGURE B-8. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IIA; OCTOBER 3, 1976
ENERGY AVERAGE OF ALL TESTS ON TEST TRACK SEGMENT
CAR INTERIOR NOISE - OVER TRUCK

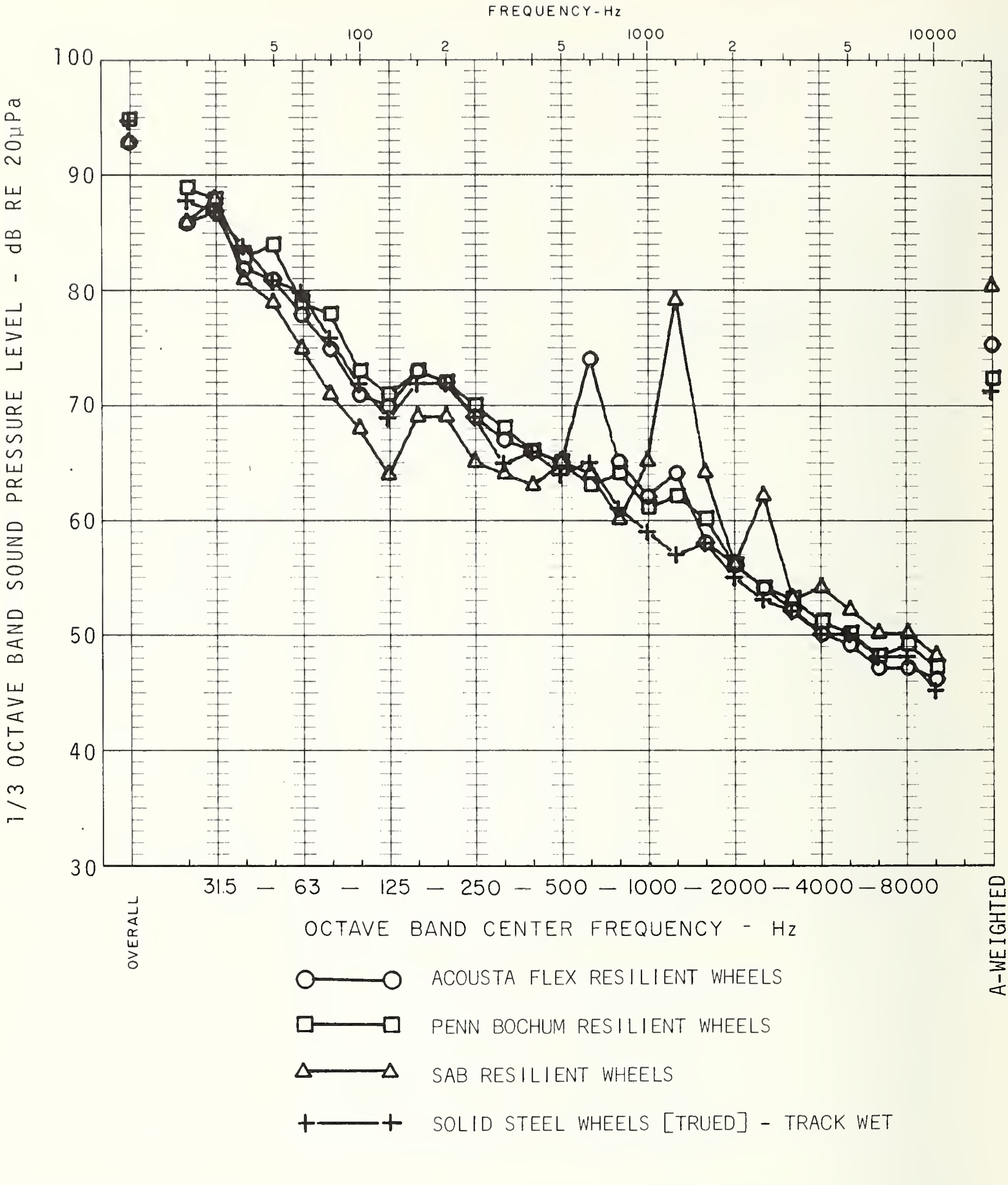

FIGURE B-9. SHORT RADIUS CURVE AT 69TH STREET TURNAROUND
PHASE IIA; OCTOBER 3, 1976
ENERGY AVERAGE OF ALL TESTS ON TEST TRACK SEGMENT
CAR INTERIOR NOISE - CAR CENTER

APPENDIX C

REPORT OF NEW TECHNOLOGY

A detailed review of work performed under this contract and the material contained in this report has not disclosed any new technology. However, the work reported here represents improved engineering data on the costs and performance of three types of commercially available urban rail noise control techniques for which such data was previously inadequate. These techniques are resilient wheels, ring-damped wheels, wheel truing, and rail grinding.