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Trees and Shrubs For Noise Abatement

by

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The Forest Service
U.S. Department of Agriculture
Cooperating With
University of Nebraska College of Agriculture
The Agricultural Experiment Station
E. F. Frolik, Dean; H. W. Ottoson, Director

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Issued July 1971, 4,200

FOREWORD

The study, "Trees and Shrubs for Noise Abatement," was a joint effort by the University of Nebraska and the U.S. Forest Service. The principal objective was to determine effective means for reducing traffic noise levels by the use of trees and shrubs, wherever intrusive noise is a problem.

Personnel serving in the project were Professor David I. Cook, Department of Engineering Mechanics, principal investigator; Dr. David F. Van Haverbeke, Research Forester, Rocky Mountain Forest and Range Experiment Station, USDA; and Mr. Thomas L. Young, student of Architecture and Community Planning, University of Nebraska. Data were analyzed at the University of Nebraska Computer Center under the direction of Mr. Richard L. Kiger.

Credit is due Mr. Lloyd Hayes, Assistant Director of the Rocky Mountain Forest and Range Experiment Station (retired) for efforts in getting the project underway; Ralph A. Read, Project Leader, Rocky Mountain Forest and Range Experiment Station, for assisting in preliminary studies and reviewing the manuscript; Dr. John C. Barber, Chief, Branch of Forest Genetics, Division of Timber Management Research, U.S. Forest Service, for negotiating the supporting grant by the Forest Service to the University of Nebraska, and Dean John R. Davis for assisting in the final negotiations and in the preparation of the original budget request.

Credit is also due Dr. Gordon Banerian and his staff, Office of Noise Abatement, Department of Transportation, for reviewing the report.

The Rocky Mountain Forest and Range Experiment Station is headquartered in Fort Collins in cooperation with Colorado State University. Dr. Van Haverbeke is stationed in Lincoln in cooperation with the University of Nebraska.

SUMMARY

The potential value of trees and shrubs, as determined from a study of a variety of shelterbelts and urban screen plantings in southeastern Nebraska, appears to be very good. Reductions of sound levels (attenuations) in the order of 5 to 8 decibels are common, and attenuations of 10 decibels (approximately half as loud) are not unusual for wide belts of tall, dense trees.

When the difference in level is based on a comparison of tree-shrub-grass combinations with hard surfaces, the worth of trees and shrubs is even more evident and attenuations of 8 to 12 decibels are common. Occasional reductions of 15 decibels or greater (⅓ as loud)

have been noted but these are attributed to exceptionally advantageous temporary atmospheric conditions.

The relative effects of tree species, height and belt width are discussed in some detail. In general, wide belts of tall trees are most effective. Species do not appear to differ greatly in their ability to reduce noise levels, provided deciduous varieties are in full leaf. Thus, evergreens are desirable for year-round noise screening.

Relative placement of noise screens between sound source and protected area is of great importance; a screen placed relatively close to a noise source is more effective than one placed close to an area to be protected.

Urban residential property was effectively screened from passenger car noise with a single row of dense shrubs backed by a row of taller trees, totaling a depth of 20 feet. Screening for rural areas or freeways, where large trucks account for much of the noise, requires wider belts consisting of several rows of tall trees in dense plantings. Distances of 100 feet or more between noise source and the area to be protected are therefore desirable.

Later phases of the study emphasized the desirability of combining trees with softer surfaces (grass) as opposed to hard surfaces (crushed rock, gravel, pavement) in reducing noise levels.

Trees and Shrubs For Noise Abatement

By David I. Cook[1]

David F. Van Haverbeke[2]

INTRODUCTION

Excessive noise is a form of environmental pollution. The continual increase in the community noise level during the past two decades indicates a future noise problem comparable to the current air pollution problem of our large industrial centers.

Trees and other forms of vegetation are known to have some effect on the transmission of sound but precise information on their use as noise screens is rather meager. In this study, we attempted to derive accurate, useful information for the above purpose, and to add to

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knowledge about outdoor sound propagation. Actual plantings of trees and shrubs in the form of shelterbelts and windbreaks on the Nebraska plains, and screen plantings of shrub-tree combinations within the city were studied.

Traffic noises produced by trucks, cars and city buses were recorded on magnetic tape to provide the sound source. These prerecorded sounds were played back through tree and shrub barriers and the sound level was measured behind the barriers at varying distances. This procedure was repeated at nearby locations under similar conditions, without trees, to evaluate the effectiveness of trees in reducing the noise level.

The subjective response to noise is so complicated that no single criterion has been generally accepted for evaluating the apparent loudness of all types of sounds. However, the dBA scale of the precision sound level meter, which approximates human response to loudness (See Glossary of Terms, Appendix A) has received considerable acceptance in rating broad-band noises such as from traffic. Because of its general acceptance and ease of application, the dBA scale was selected for making many of the measurements and reporting most of the results.

Results of the study are in two basic forms:

1. Curves that give the sound levels behind the tree belt at various distances from the noise source.

2. Curves that give the reduction in sound level due to the presence of trees.

Equations that predict the sound level at varying distances in terms of barrier heights and width have also been derived. These may be applied in the design of noise screens to predict the sound level at various distances from the belt of trees.

Two new areas of interest and some special tests concerning them are included in the later study phases. These areas, which were not detailed in the preliminary report (33), are the comparative effects of hard surfaces and tree-shrub-grass combinations; and in-town studies of tree-shrub combinations, and their effectiveness in reducing tire-roadway interaction noise. Relative placement of noise screens and end-distance effect have also been included, as well as the gross effect of wind on the effectiveness of trees as noise screens.

A supplementary study of the reduction of sound level within a belt of trees was conducted, for two reasons. We wanted to:

1. Compare the attenuation properties of trees with those of other media and surfaces, for longer distances than were normally available in standard-depth shelterbelts.

2. Find out how far into a belt of trees a person would need to go, before the noise level caused by a truck would be equal to the background level caused by the movement of air through the leaves in a

moderate 15 m.p.h. wind. This could be a consideration for a campsite location.

In this study, the noise source was placed 50 feet from the trees at the end of the belt. The microphone was moved lengthwise into the belt for distances up to 400 feet.

Observations and conclusions of the report discuss physical phenomena related to the study, and practical aspects in the use of trees and shrubs as noise screens. Specific recommendations for the use of belts of trees as noise screens and the results which could be expected are also included.

To help the reader make practical use of the material contained in this report, several hypothetical design problems have been worked out (Appendix B).

Review of Literature

Previous studies, cited in Appendix D, have sometimes been made with a filtered noise source, projecting sound in selected band widths or at a fixed frequency.

One study, "Jungle Acoustics" (13), was made to determine the direction of a sound source from a receiver, in an effort to locate the source of a rifle shot in the jungle. Also, it was desired to determine the reduction of sound level with distance. This was reported as being related to the difficulty of penetration into the jungle and the distance a foreign object might be seen. Greatest reduction was obtained with tall grass and very leafy vegetation.

A second study, "Sound Propagation in Homogeneous Deciduous and Evergreen Woods" (19), indicated excess attenuation of 7 dB per 100 feet at frequencies below 1000 Hz. A slight increase of sound level at three specific frequencies, suggesting resonant absorption by tree branches, was also observed.

A third study, "Survey of the Traffic Noise Problem" (31), states that a 200-foot band of woods can be quite useful in the attenuation of noise.

A fourth study, "The Influence of the Forest on the Health of Man" (32), indicates that the sound absorption of trees increases with frequency of sound waves. The study showed that a park 50 meters wide can reduce noise by 20 to 30 dB (below its source level).

A fifth study, "Propagation of Sound over Ground" (18), showed that excess attenuation was due to the refractive effects of temperature, wind gradients and ground cover and that upwind attenuation was found to exceed downwind attenuation by 25 to 30 decibels.

A sixth study, "Effect of Highway Landscape Development on Nearby Property" (20), indicated that sound levels below 68 dBA were "not disturbing" to most persons and that truck noise was the most severe highway disturbance.

Other references found in Appendix D have a lesser bearing on the present study, although they provide a background of material useful to noise studies in general.

CHAPTER I—EQUIPMENT AND FACILITIES

Selection of Test Sites

Fourteen tree belts of varying widths, heights and tree species, located within 100 miles northwest of Lincoln, Neb., were selected for the research. Many had been planted during the "Dust Bowl" days of the late 1930s and early 1940s under the Prairie States Forestry Project directed by the U.S. Forest Service. These plantings were established to protect crops, livestock, wildlife and man from the strong winds so prevalent on the Plains and to reduce the loss of topsoil by wind erosion. Relatively quiet locations, removed from major highways, were chosen so that traffic and other extraneous noises would not interfere with accurately measured broadcast sounds.

Of the 14 original belts, 7 major belts were selected for intensive study. These were considered representative of a wide range of sizes and tree species. Photographs and descriptions of these belts appear in Chapter III, where results of the majority of the tests are reported. The remaining seven belts were used for special purposes and are referred to elsewhere in the report. A limited number of in-town sites were also selected, to study the effect of screen plantings along major arterial streets.

Development of the Noise Source

Three major types of noise were selected from among several different noises initially considered. The selected types were:

1. Highway Truck Noise.
2. Arterial Passenger Car Noise.
3. Bus Stop Noise.

Aircraft, train and motorcycle noises, although considered, were not used because of greater feasibility of other methods of noise reduction in these cases.

Selected noises were recorded on magnetic tape and later analyzed in octave band widths (Fig. 1).

The analyzed noises were then compared with each other and with published spectra of similar noises, analyzed by other experimenters, to learn if the noises selected were truly representative of the particular types studied. They were found to be substantially so but, because truck noise varies considerably from truck to truck, a

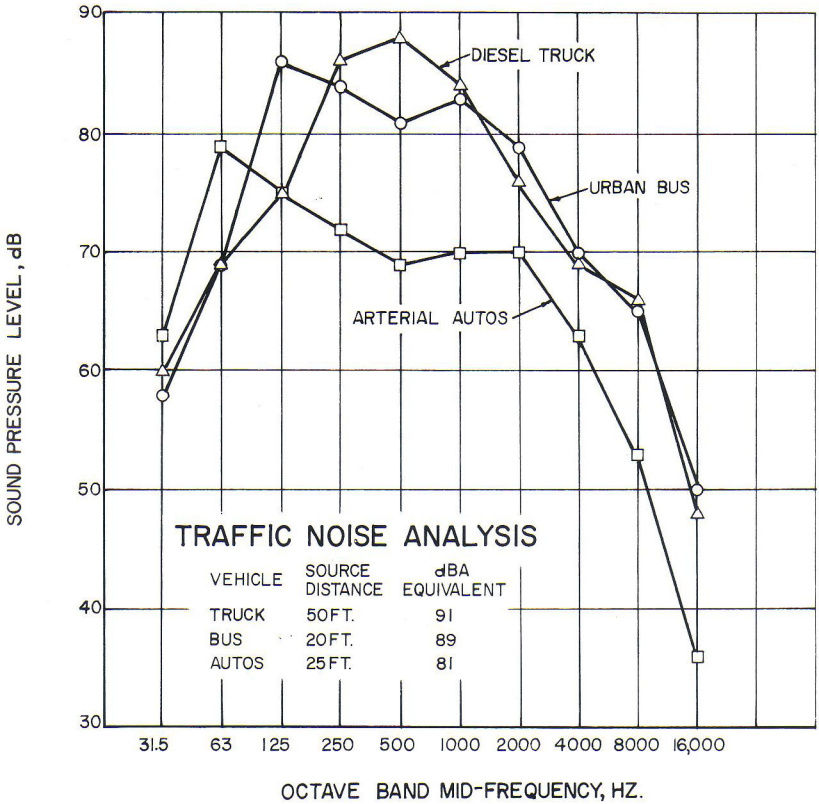

Figure 1. Noise type 1, from a diesel semitrailer, was recorded at an Interstate 80 Rest Area about 18 miles west of Lincoln, Neb. Noise type 2, from a stream of 40 m.p.h. arterial traffic, was recorded on a main street in Lincoln during the 5 p.m. rush hour. Noise type 3, from a City Lines GMC bus, was recorded at a downtown bus stop location in Lincoln.

further refinement was made in the truck noise selection. A large number of truck noises were analyzed. An average of the dB level in each octave band was taken to obtain an "average truck noise spectrum." We then selected the particular truck noise whose spectrum most nearly matched the average truck noise spectrum.

The final step in the development of the noise source was to prepare a master tape from "tape loops" of the selected noises. This master tape, containing 150 noise bursts of the three selected noises, was then used in the field. A single play of the master tape corresponded to one test run at a particular site. During the second season of tests the original truck noise was modified to increase the period of maximum noise level and to improve the accuracy of sound level measurements.

Description of Equipment

Major items of equipment consisted of a portable electric generator, a tape recorder, a high-output sound system, a magnetic tape data recorder and sound level meter, a ceramic microphone and a microphone calibrator. Meteorological equipment included thermometers, hygrometer and a wind speed and direction indicator. A commercial foam-type windscreen was used to cover the microphone. A secondary cloth-covered wire windscreen was also used to eliminate wind blast at wind velocities over 15 m.p.h. A detailed listing of the equipment[3] follows:

120 v A.C. 1600-Watt Alternator—Sears Roebuck Model 580.5508.1
Tape Recorder and Playback unit Ampex model 602
Audioamplifier 175 watt; Altec No. 1520-B
Driver Loudspeaker 100 watt, Altec No. 290-D
Multicellular Horn—Altec No. 203-B
Bass Reflex Sound Cabinet—Altec No. 825 w/515 speaker
Crossover network—Altec No. N500-C
Data Recorder—General Radio No. 1525A
Microphone—General Radio Type 1560-P5
Octave Band Analyzer—General Radio Type 1558BP
Sound Level Calibrator, General Radio Type 1562-A
Windscreen, Electro-Voice Type 524-A

CHAPTER II—RESEARCH APPROACH AND PROCEDURE

Experimental Procedure

To evaluate noise reduction, a prerecorded noise was first projected through belts of trees and shrubs and the attenuated (reduced) sound was measured at various distances behind the belts. The same prerecorded sound was then projected over similar surfaces, without the trees, to determine how much of the attenuation was attributable to the belt of trees and shrubs.

Precision equipment was used throughout, to assure high-fidelity reproduction and accurate measurements of the projected sound. Output levels were checked before each test run and sound level meters were checked frequently with a commercial sound level calibrator. The noise source consisted of a low-frequency bass reflex cabinet and high-frequency sectoral horn with a cutoff at 500 Hz (cycles per second), giving an overall flat-response characteristic from 35 to 22,000 Hz for the system.

[3] Trade names and company names are used for the benefit of the reader and do not imply endorsement or preferential treatment by the U. S. Department of Agriculture or the University of Nebraska.

The system was driven by a 135-watt amplifier, which provided ample power for the output levels required. For most of the tests the center-lines of the low-frequency speaker and high-frequency horn were located 4 and 6 feet, respectively, above the ground surface. A microphone height of approximately 5.5 feet was used for all measurements. Truck noise at a sound level of 91 dBA, measured 50 feet from the source, was adopted as a reference for most of the tests.

The sound was projected toward belts of trees and shrubs of different heights, depths and densities, at right angles to the belt; distances of 25 and 50 feet in front of the belt were used in most instances. The right angle projection was chosen as representing the worst condition of a traffic noise disturbance. Angular projections would represent a more favorable noise condition, because the transmission distance and the effective screen depth would be greater than that of the right angle projection. The sound level was then measured at distances of 25, 50, 75, 100, 150, 200, 250 and 300 feet behind the trees. Measurements of sound level (dBA) and sound pressure level (dB flat response) were recorded.

The sound projection was essentially from a point source, giving spherical divergence of sound, which corresponds approximately to a single vehicle parked at the location of the loudspeaker system. This is distinguished from a line source, giving cylindrical divergence of sound, which corresponds approximately to a continuous stream of closely spaced vehicular traffic.

Later phases of the investigation included an extended study of truck noise in a rural environment. In this study, the effect of combinations of trees, grass and other soft surfaces on noise reduction, when compared to semihard surfaces (gravel road with grass shoulder) and very hard surfaces (asphalt or concrete highways) was of primary concern.

Also included was a limited study of "in-town" noise screening with prerecorded passenger car traffic noise and bus stop noise. Actual passenger car noise was also used in one of the tests and a correlation coefficient of 0.95 was found between taped and actual noise sources. Five to 10 readings at each microphone position were averaged. The maximum "needle swing" on the meter was taken as a basis for each reading. Tape recordings were also made at each microphone position for later evaluation and analysis in the laboratory.

For certain adaptable test sites, the noise source was placed at distances of 25 to 400 feet from the front of the belt, in efforts to determine the optimum placement of trees between the noise source and a location to be protected.

Control test runs (no trees present) were designed to duplicate as nearly as possible the physical conditions of the regular test runs, so that the effects of trees alone could be observed. Control runs were

made immediately preceding or following regular test runs, to minimize the effect of any possible change in atmospheric gradients. Also, nearby locations with similar terrain were used, where possible, to minimize the effect of different topography and surface conditions. Where a similar surface was unavailable, a correction in sound level was applied to account for the different effects of the test run surface. Special tests were run to obtain "surface correction factors" for these cases.

Measurements of sound levels at wind velocities over 15 m.p.h. were found to be unreliable and were avoided where possible. All data used were for relatively low wind velocities, below 10 m.p.h. in most cases, and all tape recordings were made at wind velocities below 7 m.p.h. "Attenuation" or "difference" curves, which were derived from averages of a number of readings for each belt studied, were also plotted by computer to show:

1. The difference in sound level with and without the presence of trees.
2. The probable overall effect of different tree belt configurations on the reduction of noise.

These computer-plotted curves were omitted from the report in favor of hand-drawn curves, described below.

Hand-drawn curves, adjusted for minor experimental variations and control surface variation by the process of fairing, were also prepared. These new curves gave the sound level and attenuation (measured behind the trees) at various distances from the noise source and were planned for ease of reading and direct selection of tree belts for noise screening. Graphs containing these curves appear in Chapter III.

Only a limited statistical analysis of the test results was made for survey purposes, since the primary objectives of the study were not statistically oriented. The procedure used followed the standard multiple regression analysis procedures of statistics wherein a relationship among a single dependent variable and several independent variables is obtained. An equation giving this relationship and some indication of the relative significance of each variable is also provided.

CHAPTER III—RESULTS OF EXPERIMENTS

Major Belt Tests

Each of the seven major tree belts studied is illustrated in a photograph, a descriptive schematic drawing and graphs of the noise reduction characteristics of the belt (Figs. 2-19). The graphs show the sound level, measured behind the trees, in dBA units, at distances up to about 450 feet from the noise source.

TABLE OF BELT DESCRIPTIONS

Belt no.	Tree height (feet)	Belt depth (feet)	Composition	Page no. reference
2 P	60	90	9-Row Deciduous	44
2 PL	17	67	6-Row Blue Spruce	12
5 P	45	50	2-Row Eastern Redcedar	14
13 Y	30	63	4-Row Eastern Redcedar	16, 31, 38
15 Y	45	100	9-Row Mixed Conif.-Decid.	19, 32, 34, 39
19 S	45	100	10-Row Mixed Conif.-Decid.	21, 33, 37, 40
30 P	58	120	10-Row Mixed Conif.-Decid.	24, 41
38 S	30	45	3-Row Mixed Conifer	27, 42, 58
19 P	38	75	1-Row Eastern Redcedar, 3-Rows Pine	35
Valley Road	18	20	1-Row Shrub, 1-Row Pine	49, 52

Common and scientific names of plants mentioned in the above table and elsewhere in the report are listed in Appendix C.

Each of the three noises used in the experiments is represented by an individual curve. The sound level at any desired distance from the noise source may be read directly from the curve. A set of three "excess attenuation" curves is drawn below the sound level curves to show the reduction in sound level caused by the trees. These are termed "excess attenuation" curves because they show the reduction in sound level due to the presence of trees in excess of the natural attenuation due to distance, atmospheric absorption, ground absorption and other effects. The curves represent the average of a number of tests made during the summer of 1969 at noise source distances of 50 feet from the front edge of the tree belt.

A supplementary series of 25-foot source distance tests was also run at certain adaptable test sites, although we recognized that placement of trees 25 feet from a high speed traffic lane is generally not recommended for safety and other reasons. However, there are certain instances where the smaller distances might be advantageous, for example, in residential areas where speed limits are lower and where a row of dense shrubs is planted nearest the roadway, in front of the taller trees. A graph for each 25-foot source distance test is shown immediately following the 50-foot graph for the same belt.

A single curve for truck noise with no trees present is shown on the graphs for comparison. A theoretical point source sound projection curve is also shown for reference. The equation, which also appears in Chapter IV under "Factors Affecting Noise Reduction" is:

$$S_d = S_o - 20 \log \frac{d}{d_o}$$

where:

d = the prescribed distance from the noise source

d_o = a reference distance where the sound level is known
S_d = the sound level (dBA) at the prescribed distance from the noise source
S_o = the sound level (dBA) at the reference distance.

The reader is encouraged to consult the Glossary of Technical Terms (Appendix A), as necessary, for an understanding of the results of the experiments.

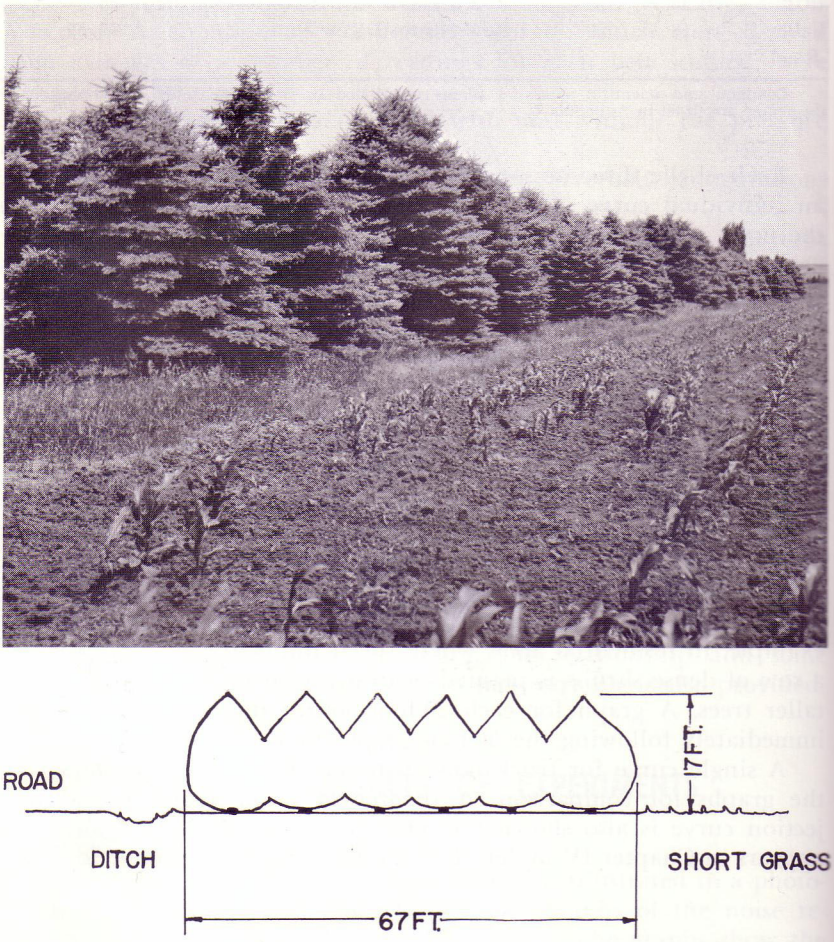

Figure 2. Belt No. 2PL, Donald F. Schwarz Farm. Six rows of blue spruce 17 ft. tall; between-row spacing 10 ft., in-row spacing 10 ft., belt width 67 ft.

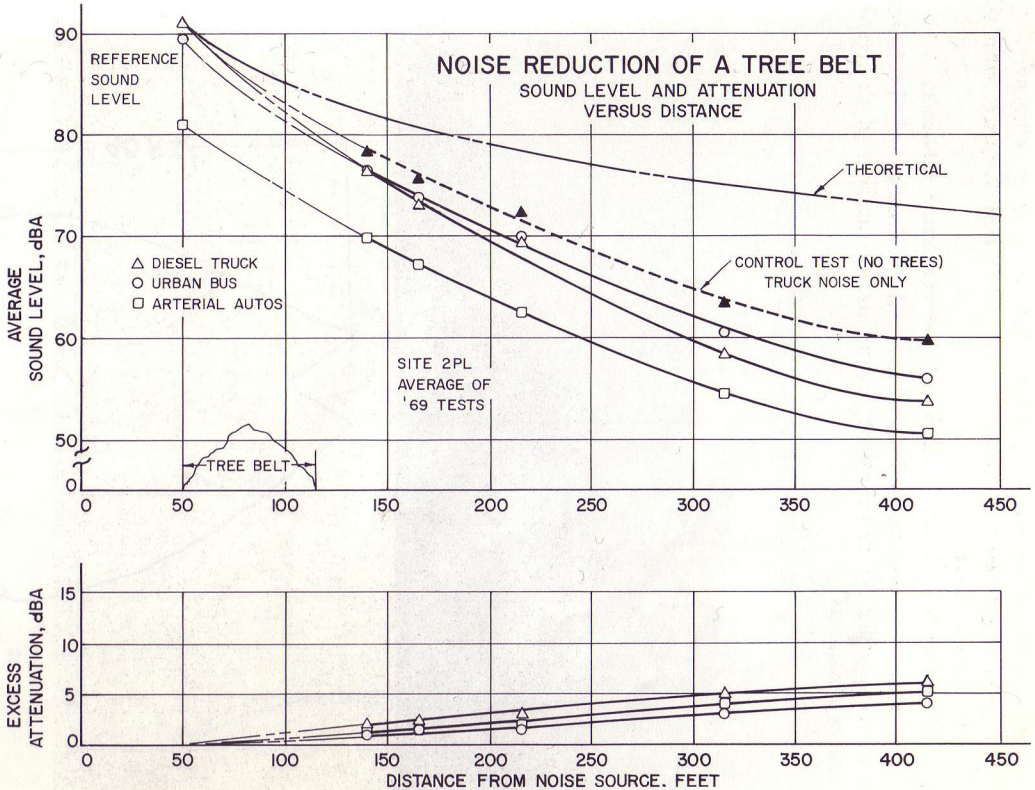

Figure 3. Site 2PL, average of '69 tests.

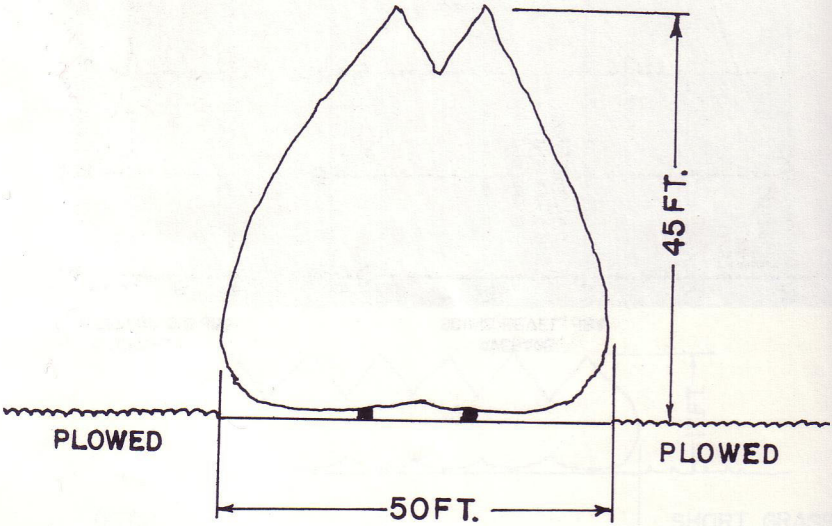

Figure 4. Belt No. 5P, Augustin Bros. farm. Two rows eastern redcedar 45 ft. tall; between-row spacing 8 ft.; in-row spacing 8 ft.; belt width 50 ft. The cornfield shown in the foreground was a plowed surface when the tests were run.

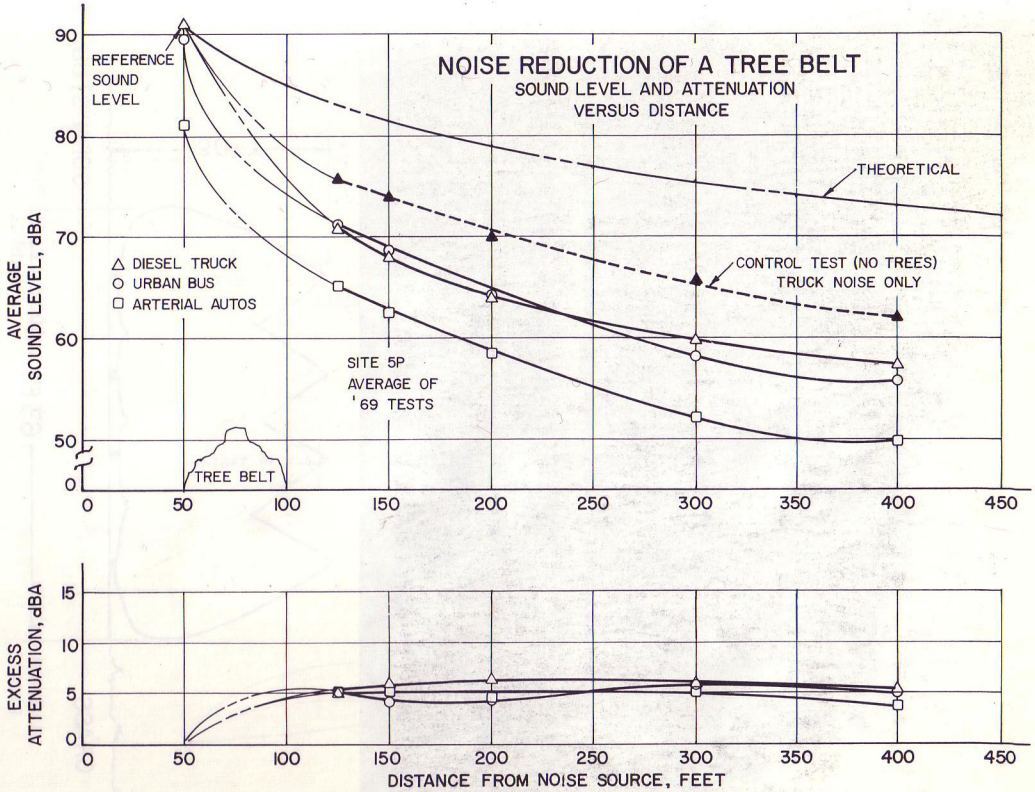

Figure 5. Site 5P, average of '69 tests.

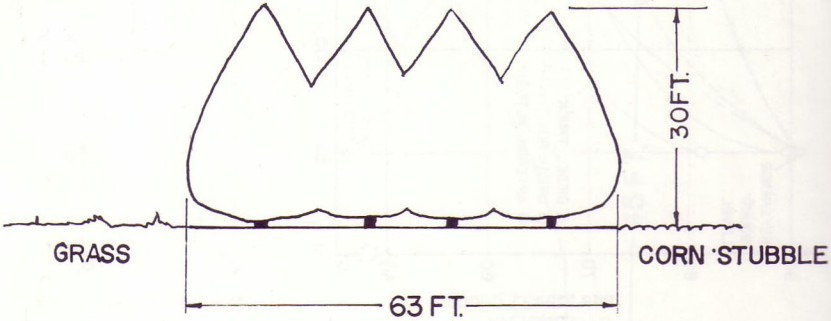

Figure 6. Belt No. 13Y, Lloyd McLain farm. Four rows eastern redcedar 30 ft. tall; between-row spacing 12 ft.; in-row spacing 9 ft.; belt width 63 ft.

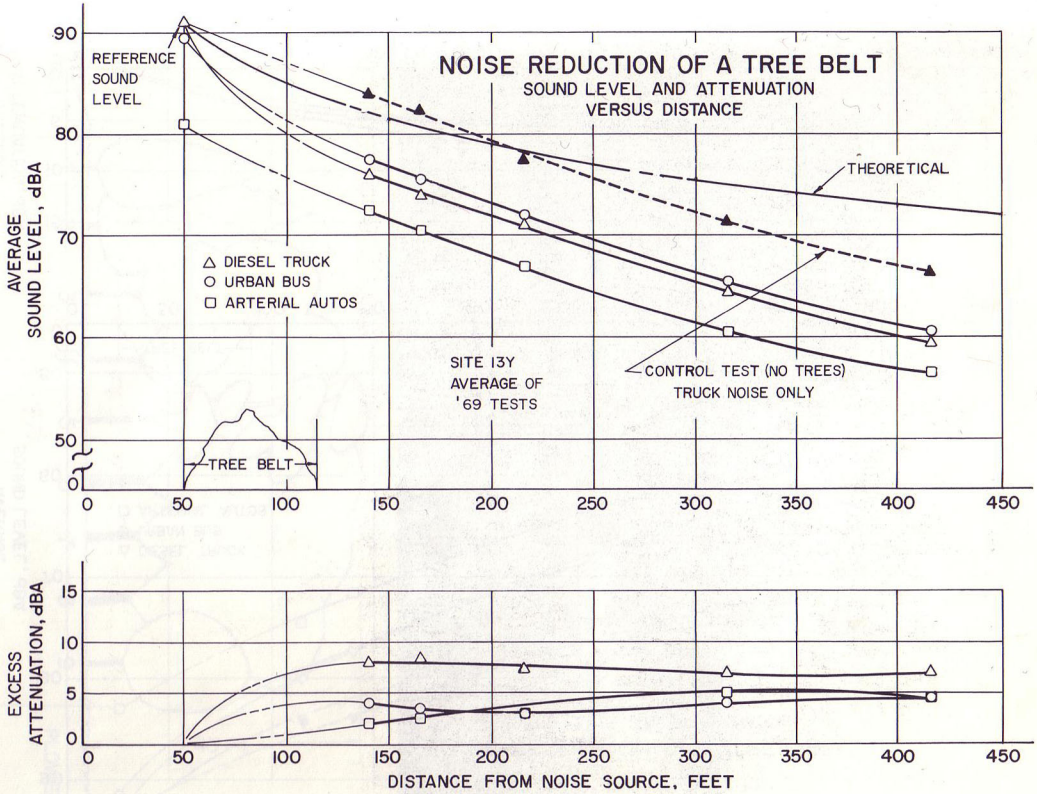

Figure 7. Site 13Y, average of '69 tests.

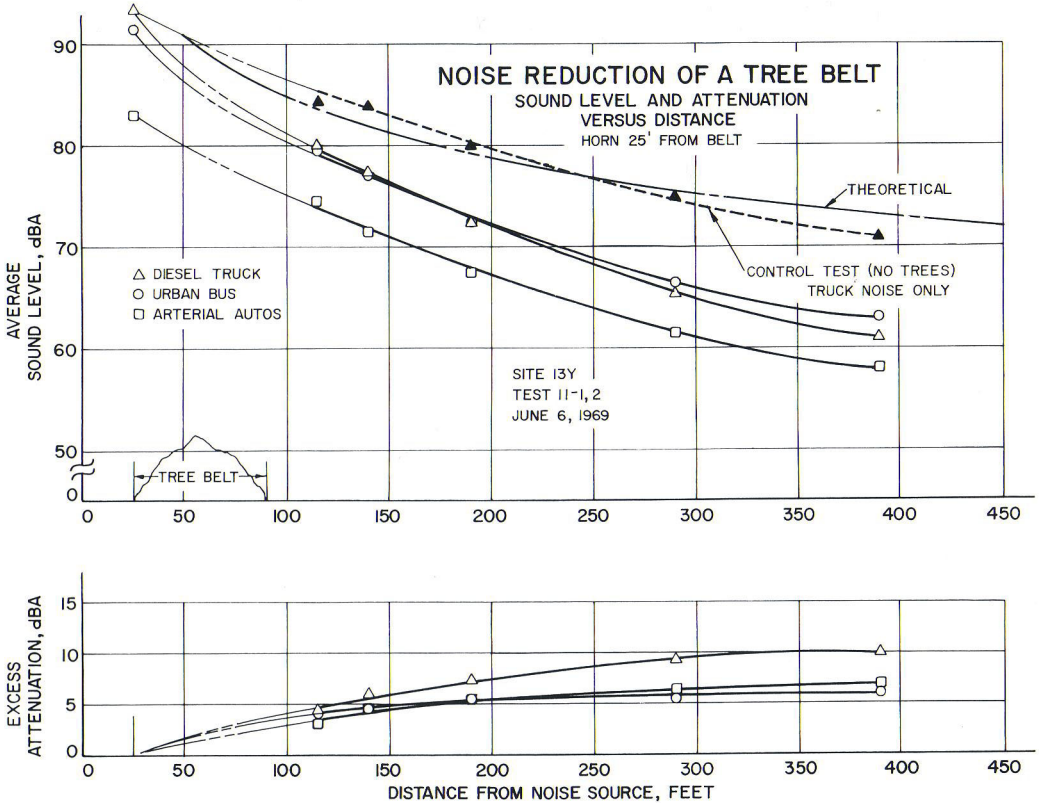

Figure 8. Site 13Y, test 11-1, 2, June 6, 1969.

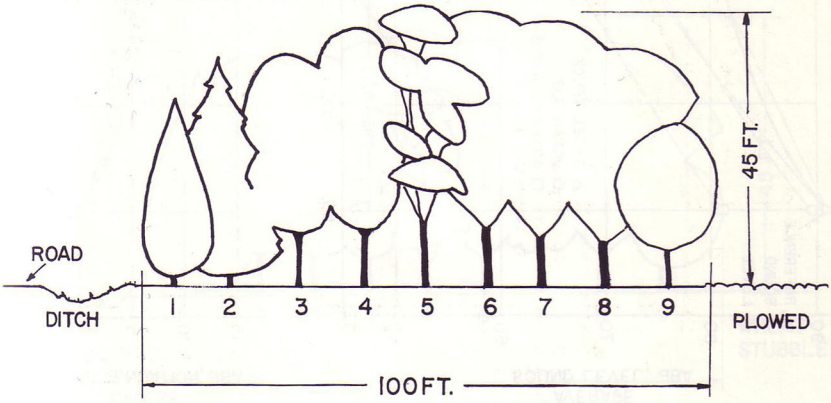

Figure 9. Belt No. 15Y, Irvin and Helen Rafert farm. Nine row belt S. to N. 45 ft. tall; 1. Eastern redcedar. 2. Ponderosa pine. 3. Green ash. 4. Hackberry. 5. Honey Locust. 6. Siberian elm. 7. Siberian elm. 8. American elm. 9. Mulberry. Between-row spacing 10 ft.; in-row spacing 6 ft.; belt width 100 ft.

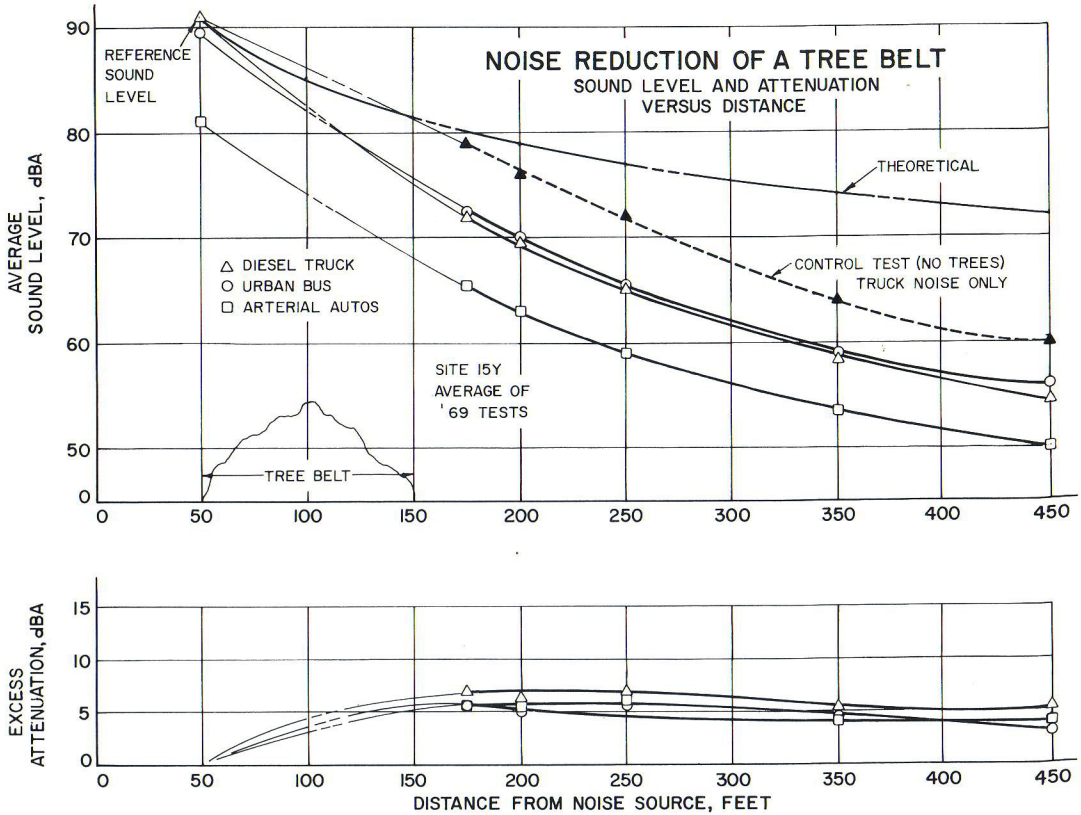

Figure 10. Site 15Y, average of '69 tests.

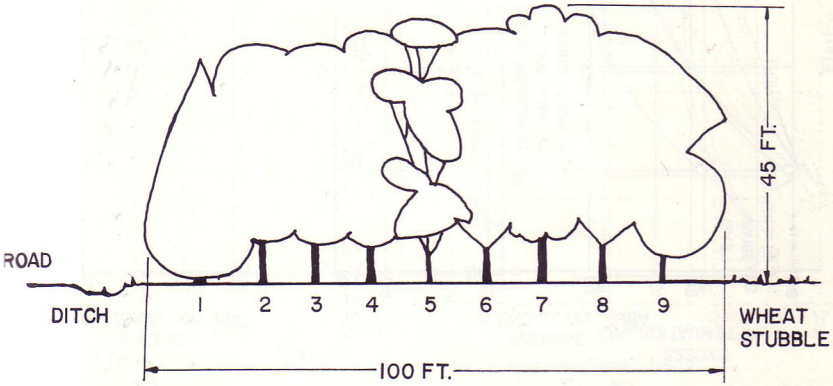

Figure 11. Belt No. 19S, Hackbart farm. Ten row belt, S. to N. 45 ft. tall. Russian-olive (cut)-(not shown); 1. Eastern redcedar. 2. Green ash. 3. Green ash. 4. Hackberry. 5. Honey Locust. 6. Siberian elm. 7. Cottonwood (thinned). 8. Siberian elm. 9. Mulberry. Between-row spacing 10 ft.; in-row spacing 8 ft.; belt width 100 ft.

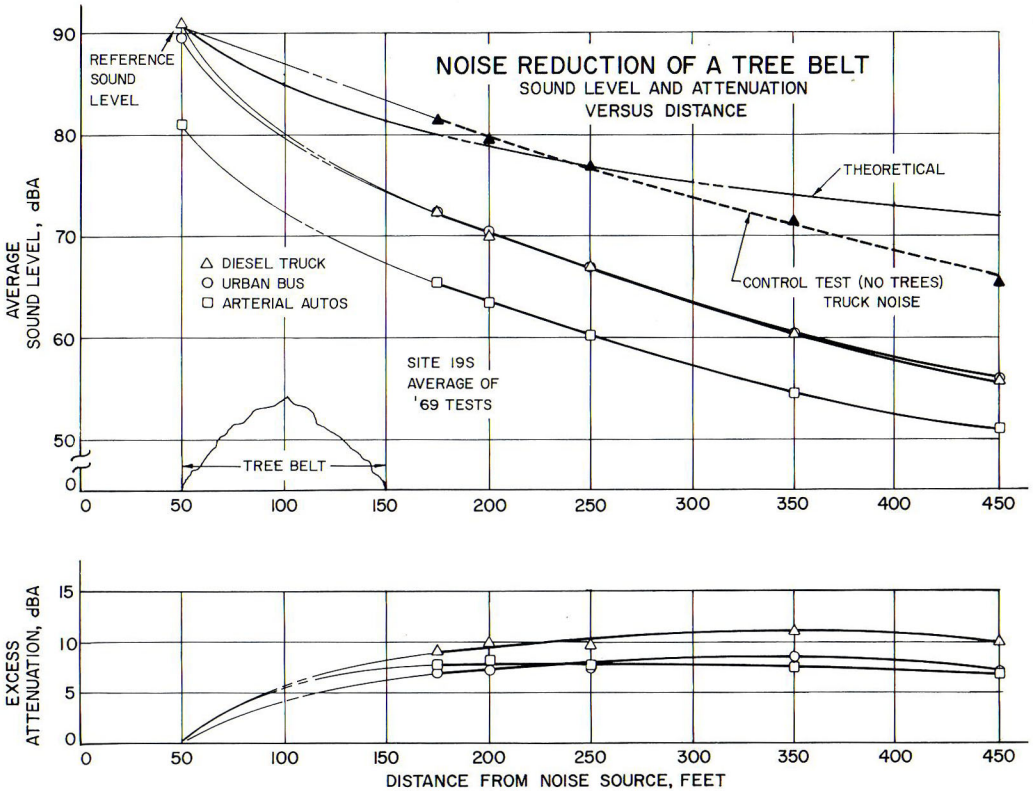

Figure 12. Site 19S, average of '69 tests.

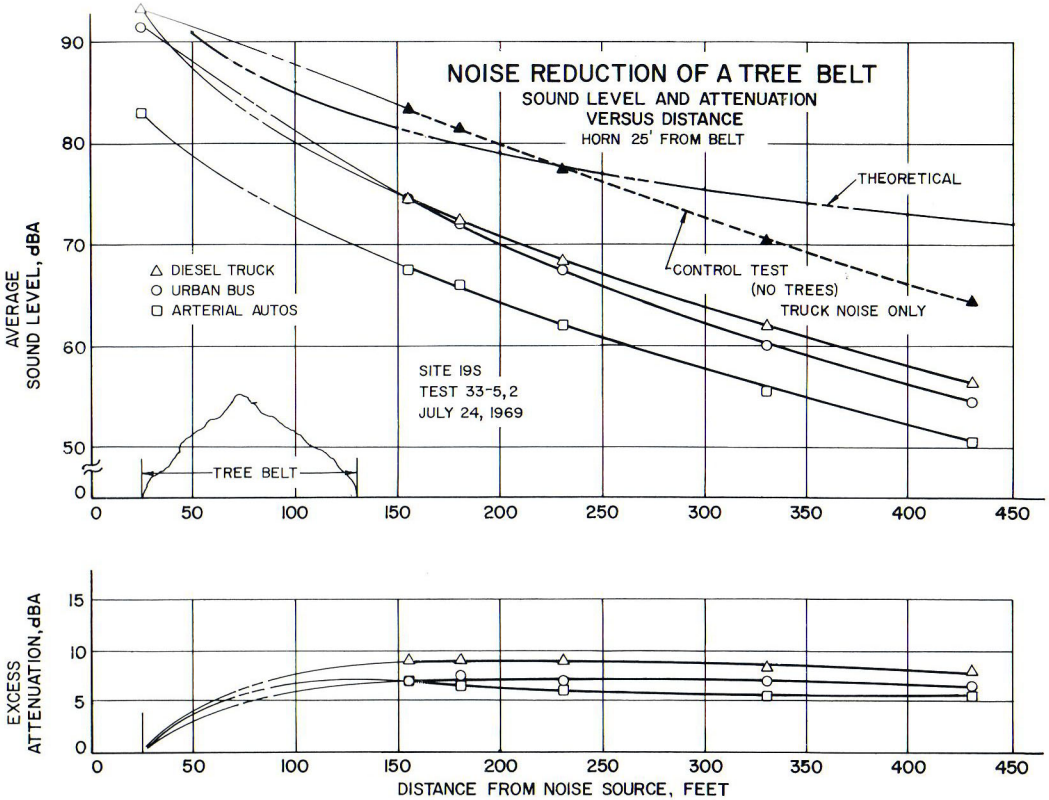

Figure 13. Site 19S, test 33-5, 2, July 24, 1969.

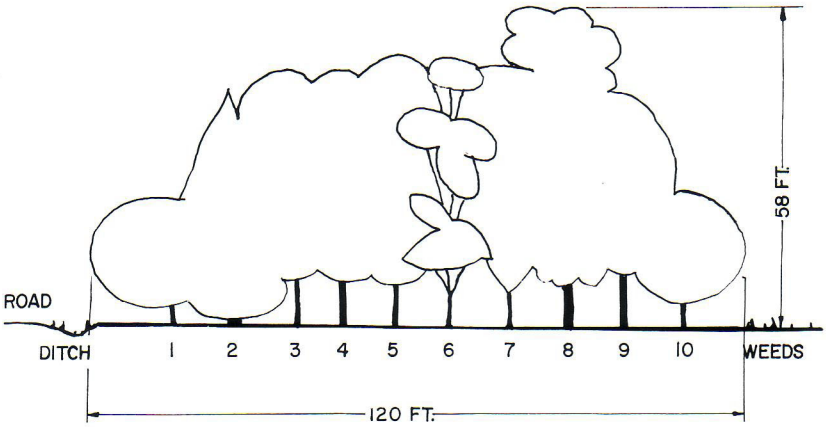

Figure 14. Belt No. 30P, Ed Dobberstein farm. Ten row belt, S. to N. 58 ft. tall. 1. Russian-olive. 2. Ponderosa pine—Eastern redcedar. 3. Green ash. 4. Green ash. 5. Hackberry. 6. Honey Locust. 7. Siberian elm. 8. Cottonwood. 9. Hackberry. 10. Mulberry. Between-row spacing 10 ft.; in-row spacing 8 ft.; belt width 120 ft.

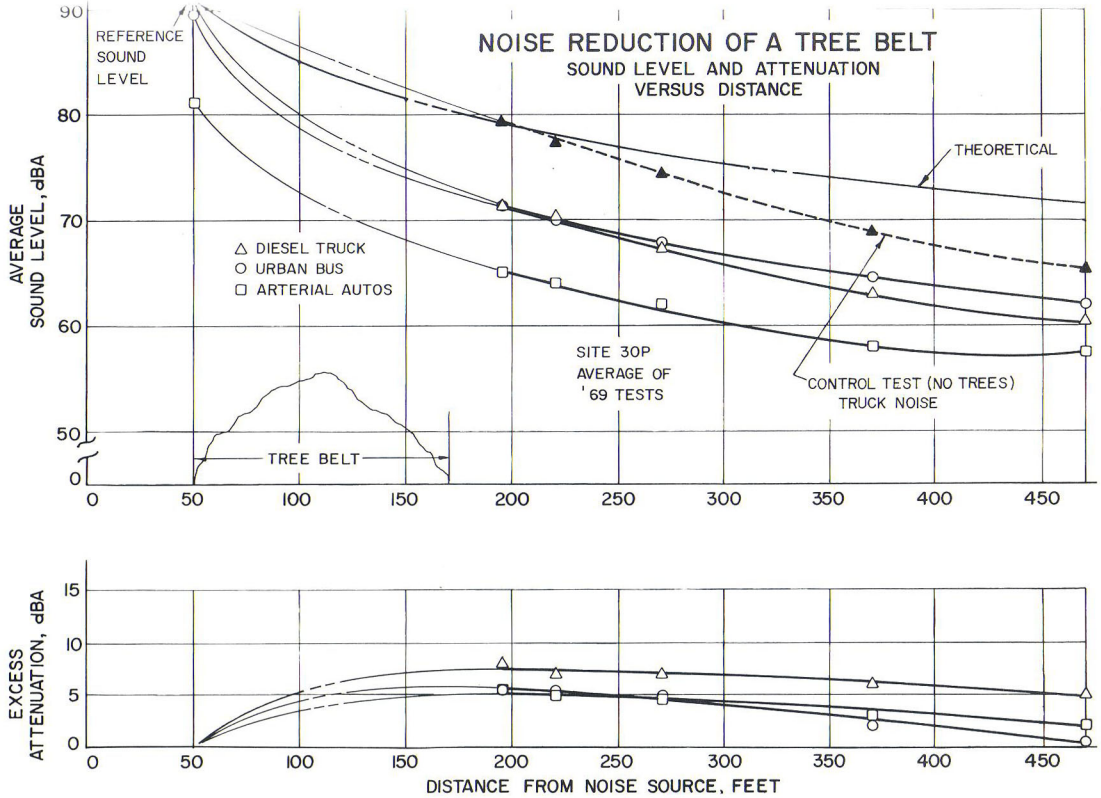

Figure 15. Site 30P, average of '69 tests.

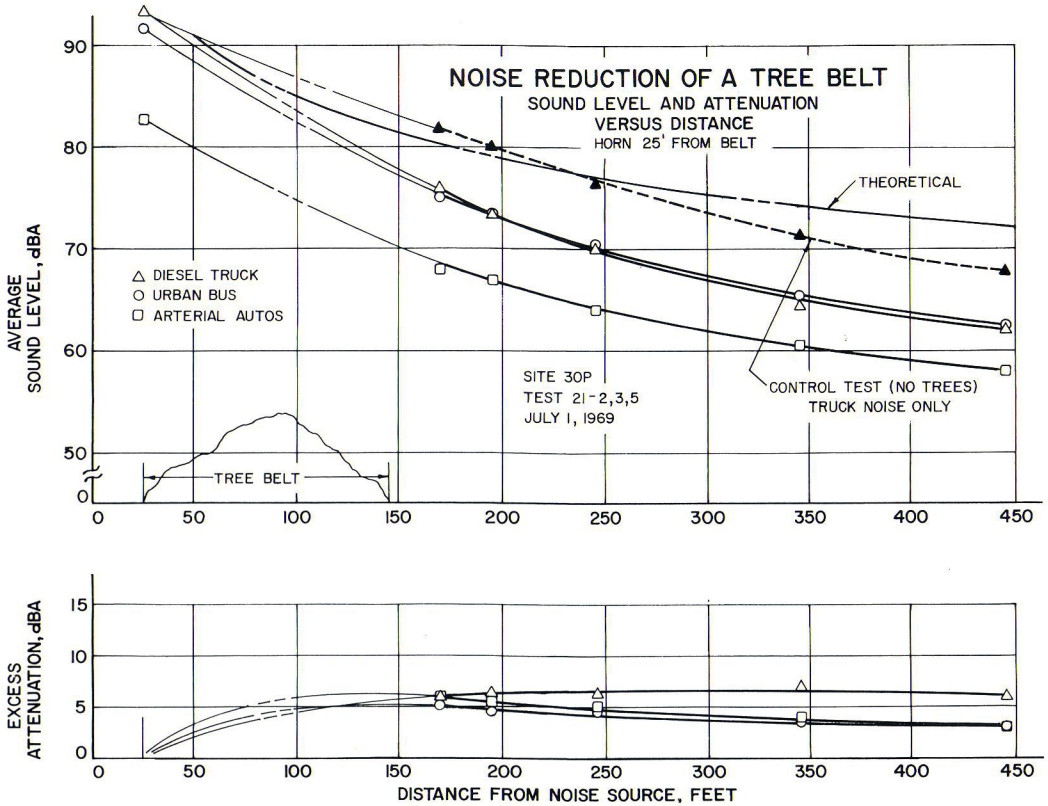

Figure 16. Site 30P, test 21-2, 3, 5, July 1, 1969.

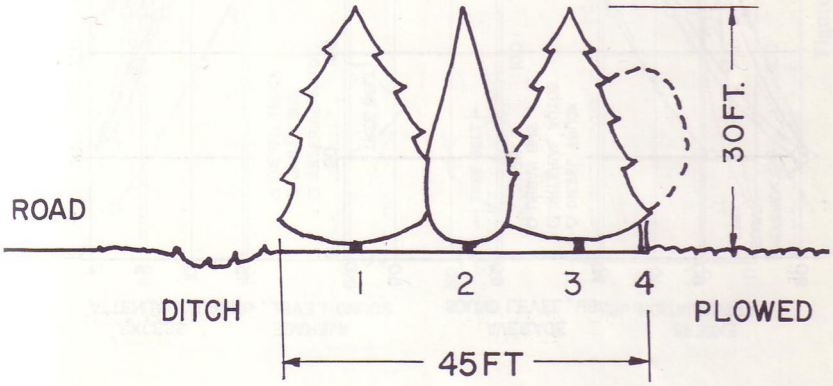

Figure 17. Belt No. 38S, Merle Schluckebier farm. Four row belt S. to N. 30 ft. tall. 1. Ponderosa pine. 2. Eastern redcedar. 3. Ponderosa pine. 4. Apricot (very thin—1 of 6 to 10). Between-row spacing 12 ft.; in-row spacing 8 ft.; belt width 45 ft.

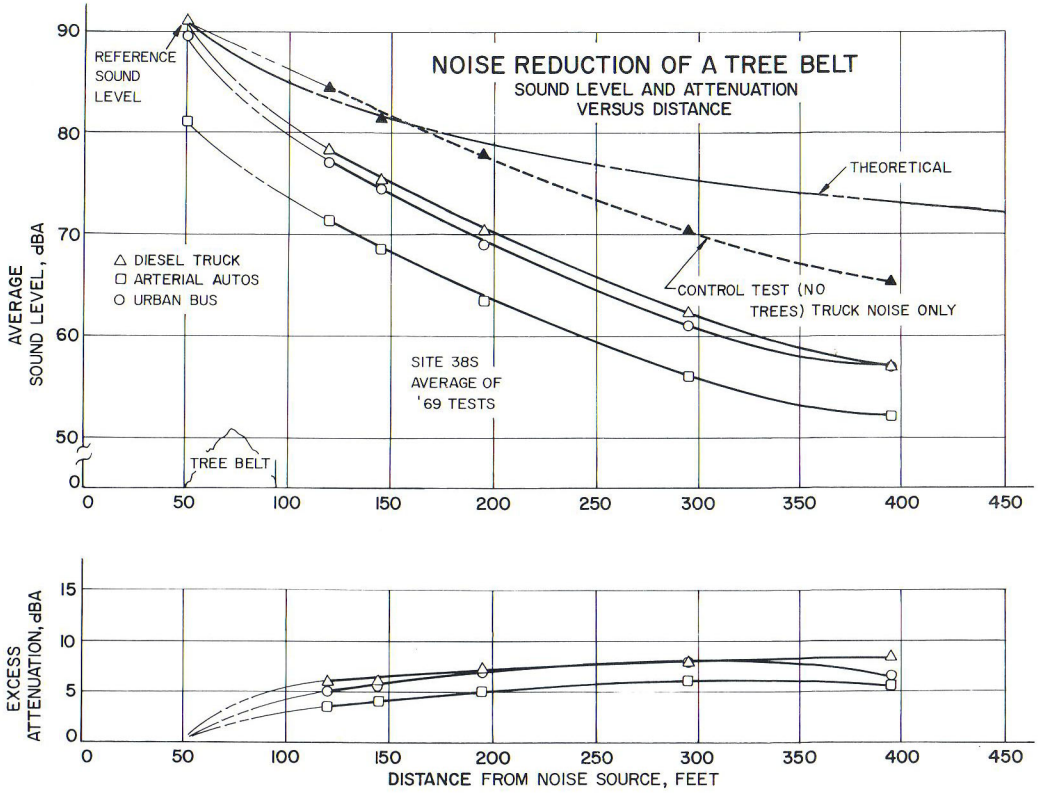

Figure 18. Site 38S, average of '69 tests.

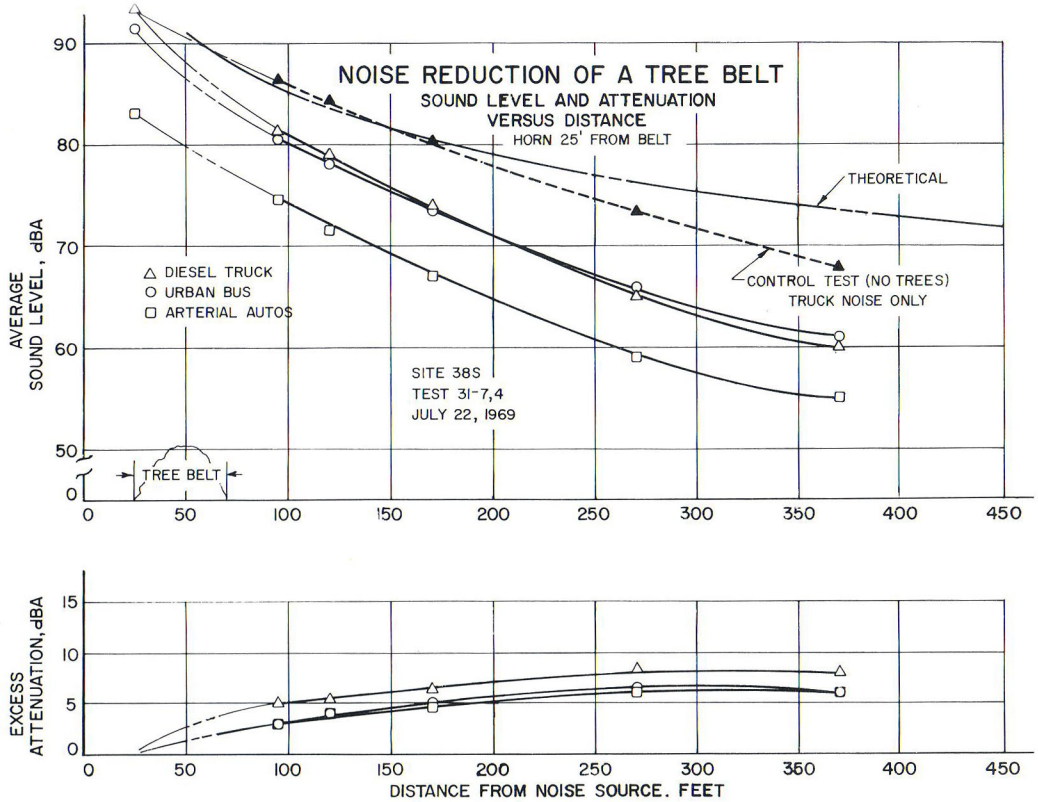

Figure 19. Site 38S, test 31-7, 4, July 22, 1969.

Comparative Surface Tests

During the early part of the study it became apparent that the type of surface over which the sound passes has a marked effect on the noise reduction (this point to be discussed in Chapter IV). We therefore projected the recorded truck noise over surfaces with various degrees of hardness and compared the attenuation with that obtained by projection through trees. The following graphs (Figs. 20-22) show the sound level, dBA units, at distances up to about 450 feet from the noise source. A set of three "relative attenuation" curves is drawn below the sound level curves. These are termed "relative attenuation" curves because they show the reduction in sound level due to the presence of trees relative to several different surfaces.

Longitudinal Propagation Within Belt

A limited study of the sound propagation lengthwise within belts of trees was made for two reasons:

1. To determine the effectiveness of continuous tree plantings in reducing noise, when compared to other surface cover.

2. To determine how far into a grove of trees one would need to go before the noise of a passing truck would be practically indistinguishable from background noise caused by moderate wind movement through the trees. This second reason would have application to camping in a wooded area.

Figs. 23 through 26 show the decrease in sound level with distance into the belt. Background sound level is also indicated. Attenuation relative to a moderately hard surface is shown on the lower curves. Data for the control test curve of Fig. 25 were obtained by projecting the sound *against* a wind of approximately 10 m.p.h. The characteristic rapid decrease of sound level upwind accounts for the relatively low attenuation attributable to the belt.

Octave Band Analysis of Selected Belts

Noise screening properties of selected belts were studied by octave band analysis. Sound levels behind the belts and adjacent to them were recorded on magnetic tape. The tape was analyzed in octave band widths. Graphs which follow (Figs. 27-31) show the analysis of sound levels behind the trees, and excess attenuation for truck noise only. Octave bands with center frequencies of 63, 125, 250, 500, 1000, 2000 and 4000 Hz. were selected for this analysis. A "flat" or unweighted curve and a dBA curve are also shown on the graphs for reference.

These graphs have been included for the benefit of those who may wish to make a more detailed examination of the results; no attempt has been made to explain the characteristics of the results, as such analysis is beyond the intent of this study.

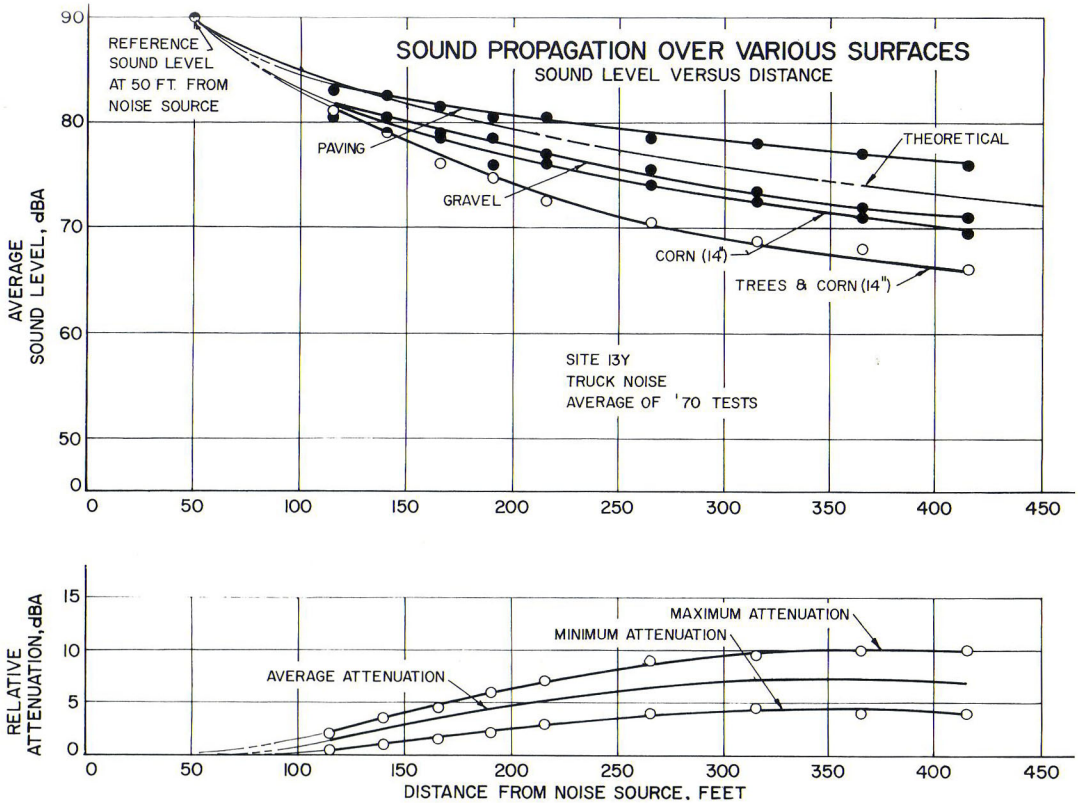

Figure 20. Site 13Y, truck noise, average of '70 tests.

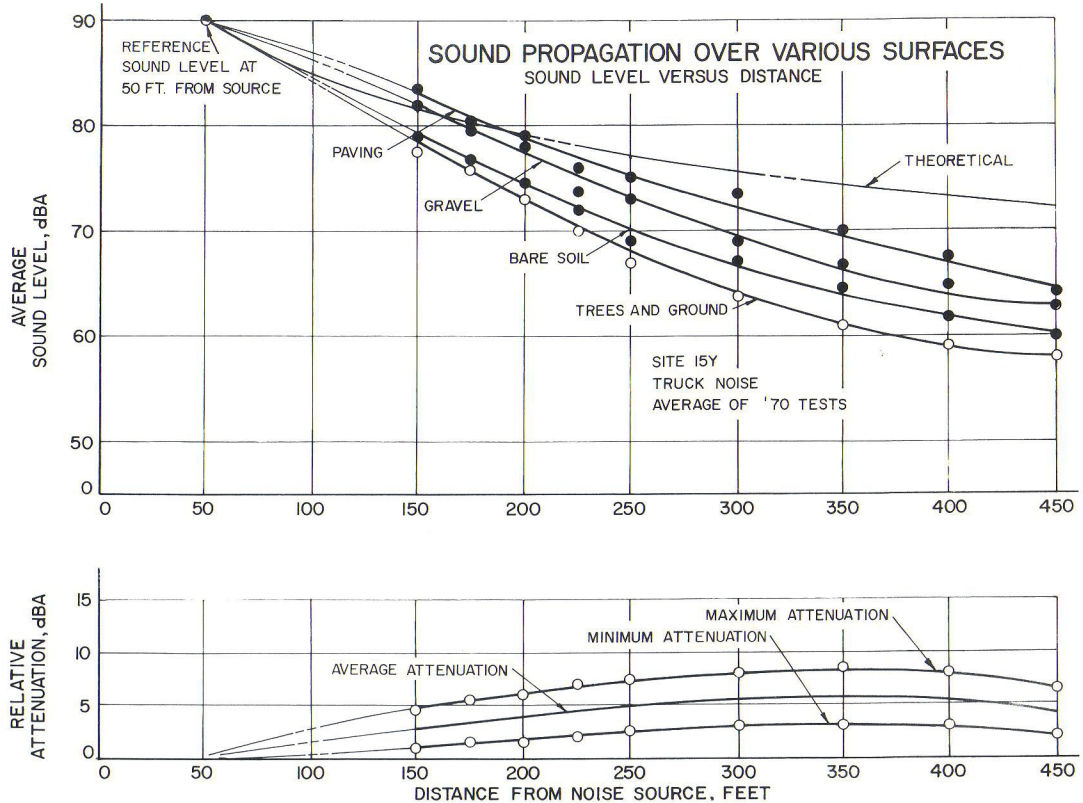

Figure 21. Site 15Y, truck noise, average of '70 tests.

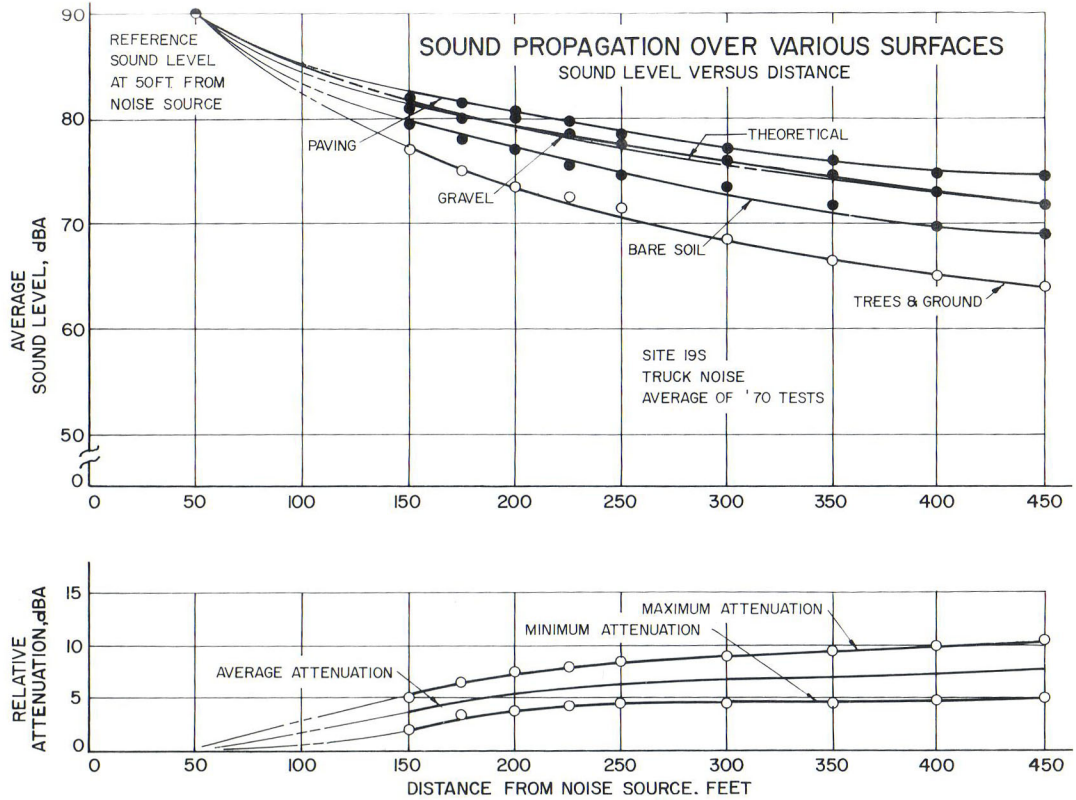

Figure 22. Site 19S, truck noise, average of '70 tests.

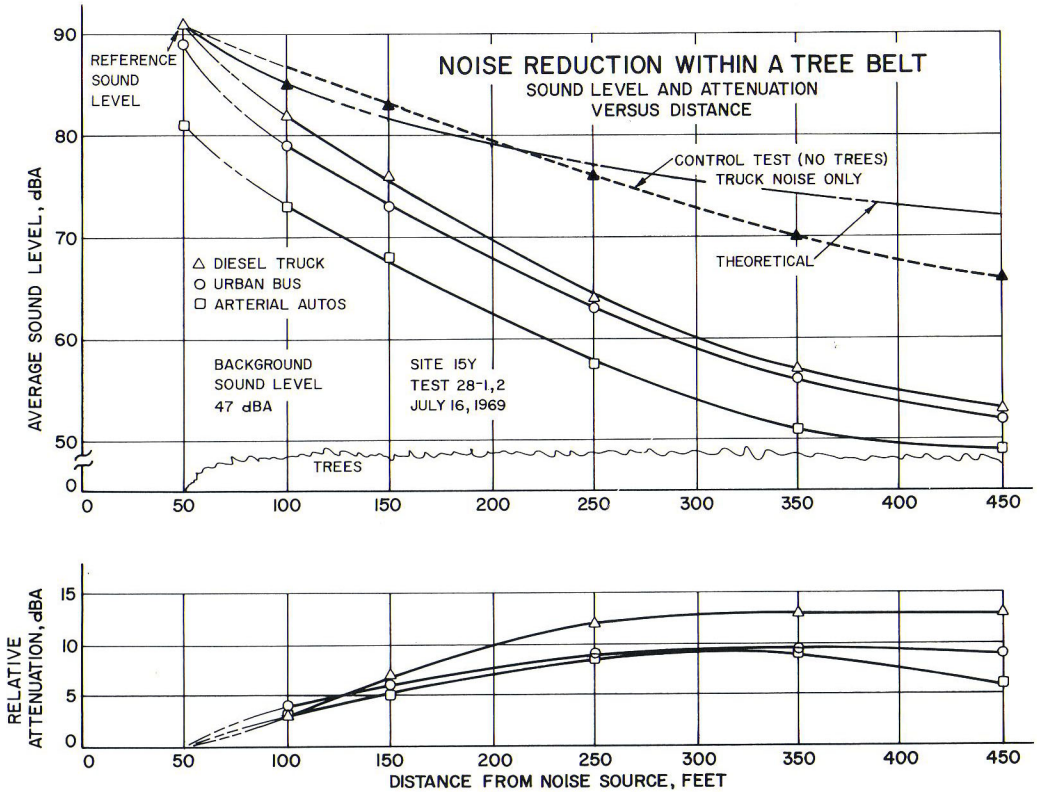

Figure 23. Site 15Y, test 28-1 2, July 16, 1969.

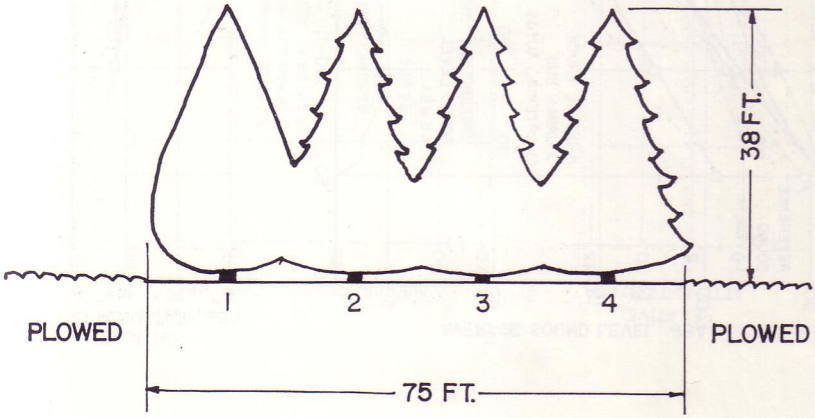

Figure 24. Belt No. 19P, Floyd C. West farm. Four row belt S. to N. 38 ft. tall. 1. Eastern redcedar. 2. Ponderosa pine. 3. Ponderosa pine. 4. Ponderosa pine. Between-row spacing 18 ft.; in-row spacing 17 ft.; belt width 75 ft.

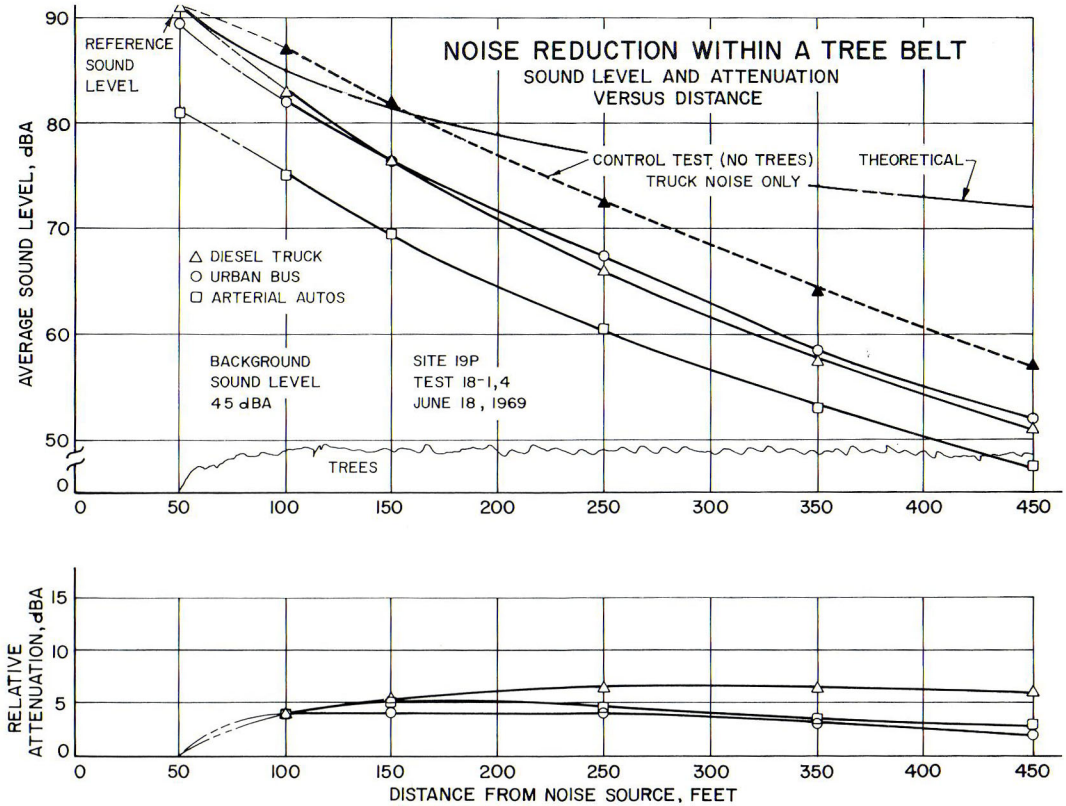

Figure 25. Site 19P, test 18-1, 4, June 18, 1969.

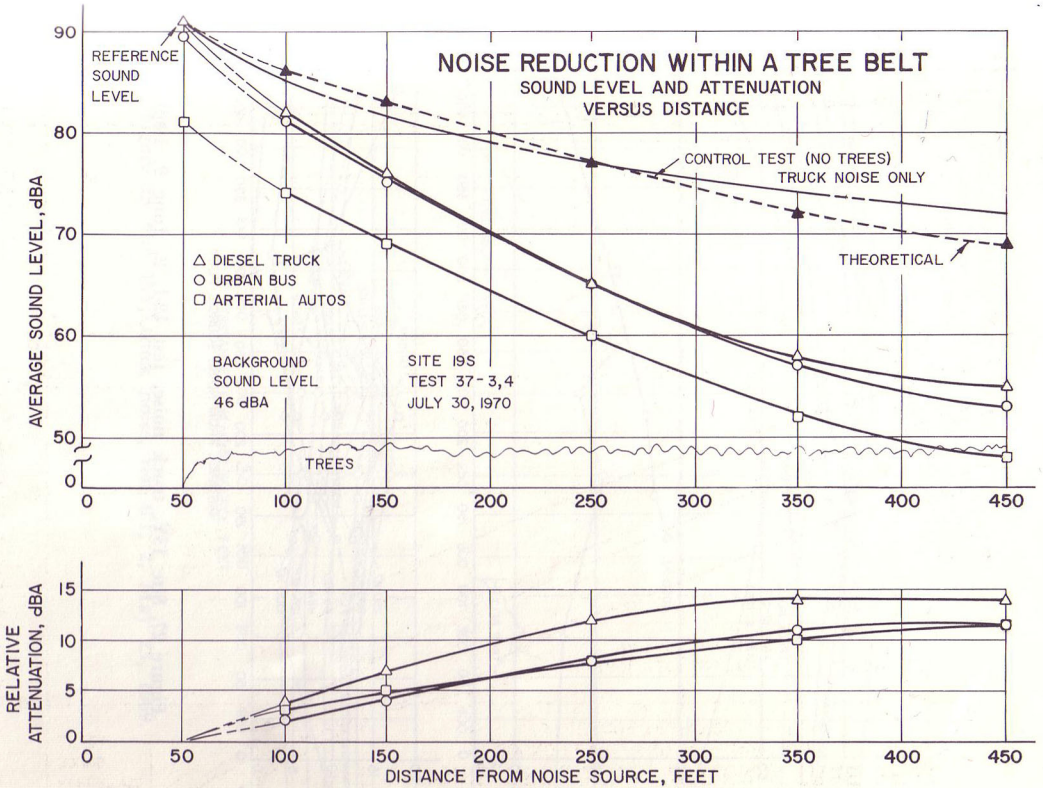

Figure 26. Site 19S, test 37-3, 4, July 30,1970.

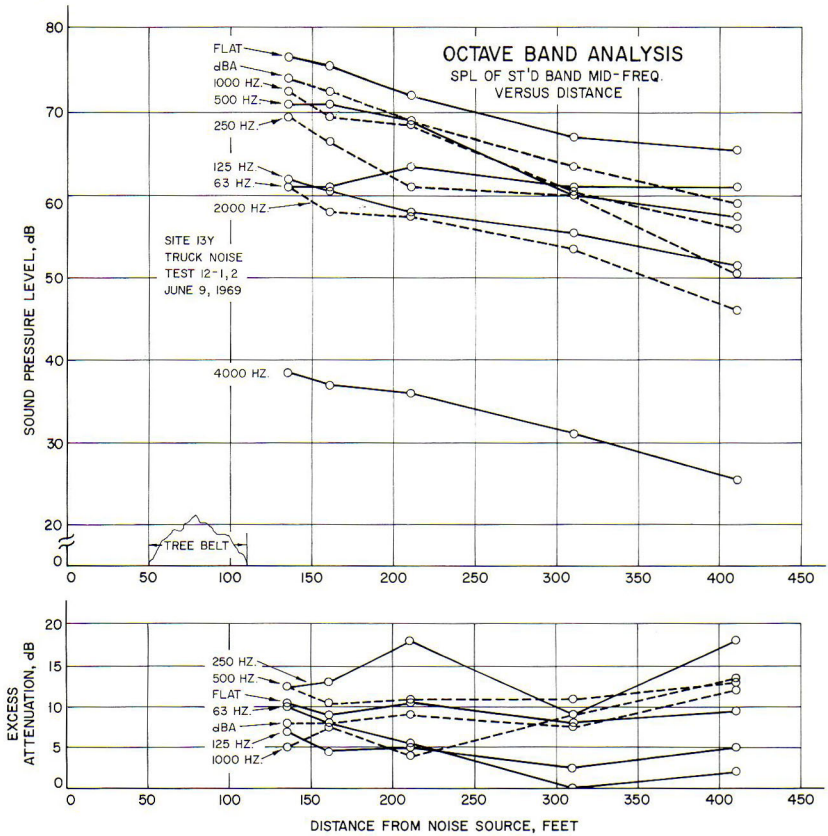

Figure 27. Site 13Y, truck noise, test 12-1, 2, June 9, 1969.

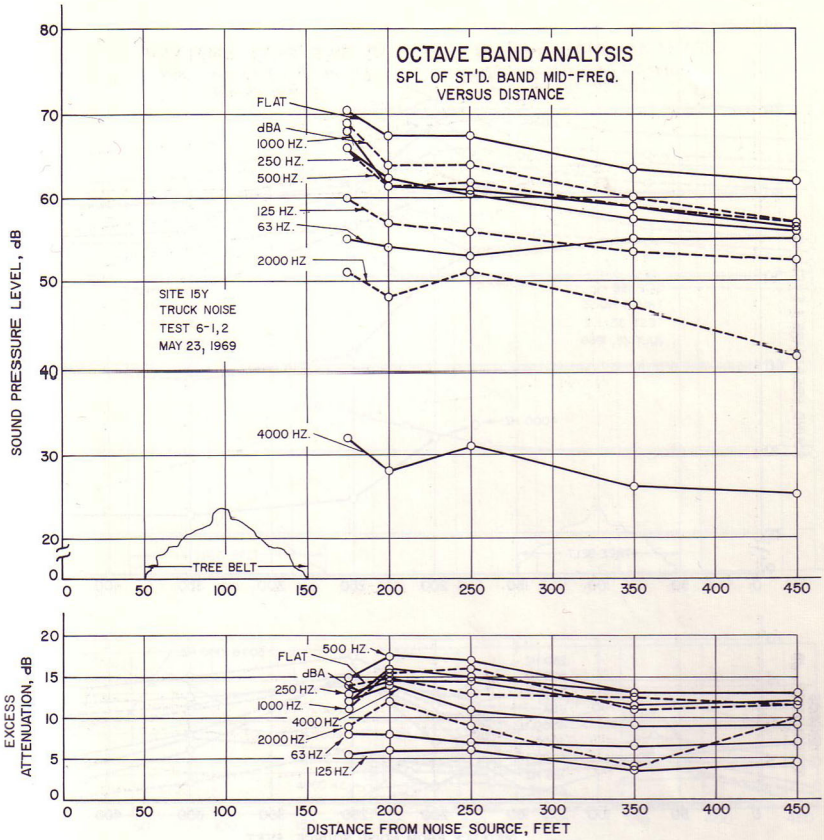

Figure 28. Site 15Y, truck noise, test 6-1, 2, May 23, 1969.

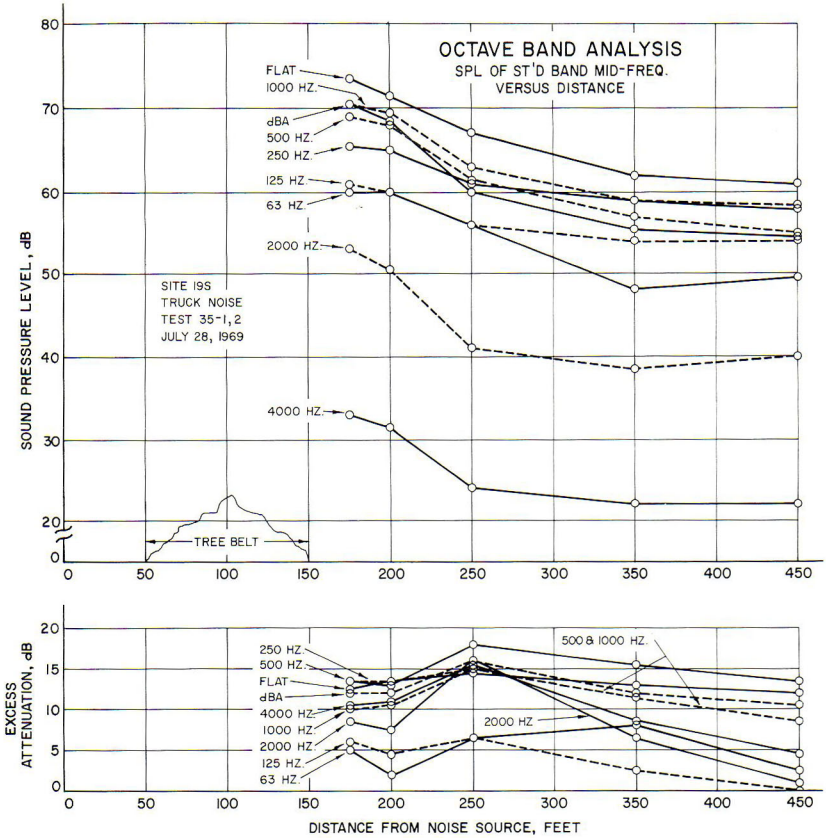

Figure 29. Site 19S, truck noise, test 35-1, 2, July 28, 1969.

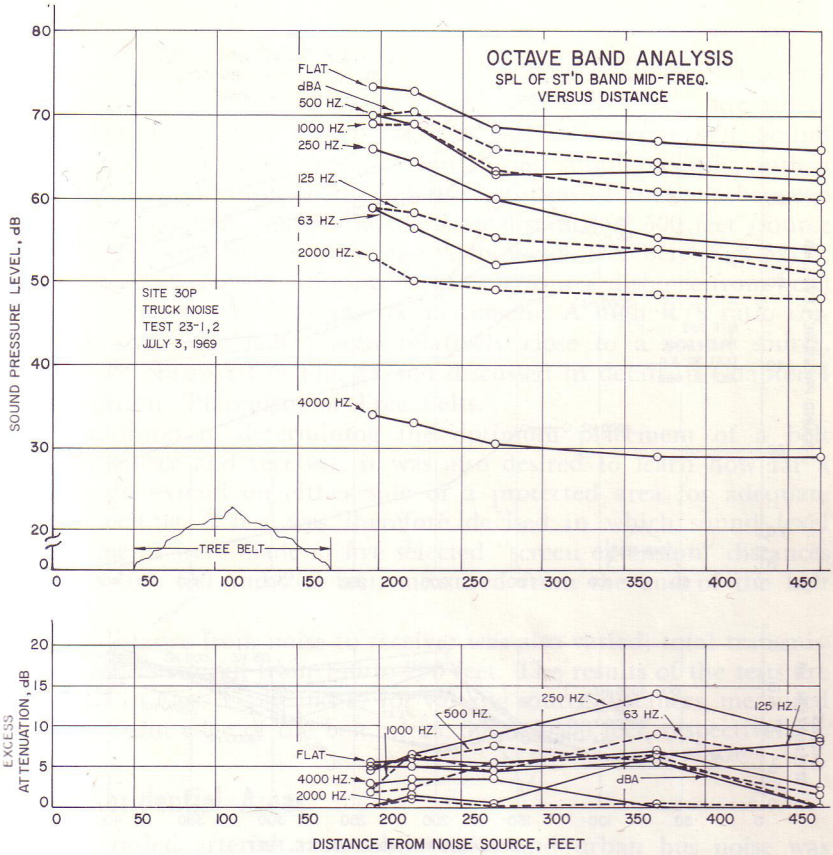

Figure 30. Site 30P, truck noise, test 23-1, 2, July 3, 1969.

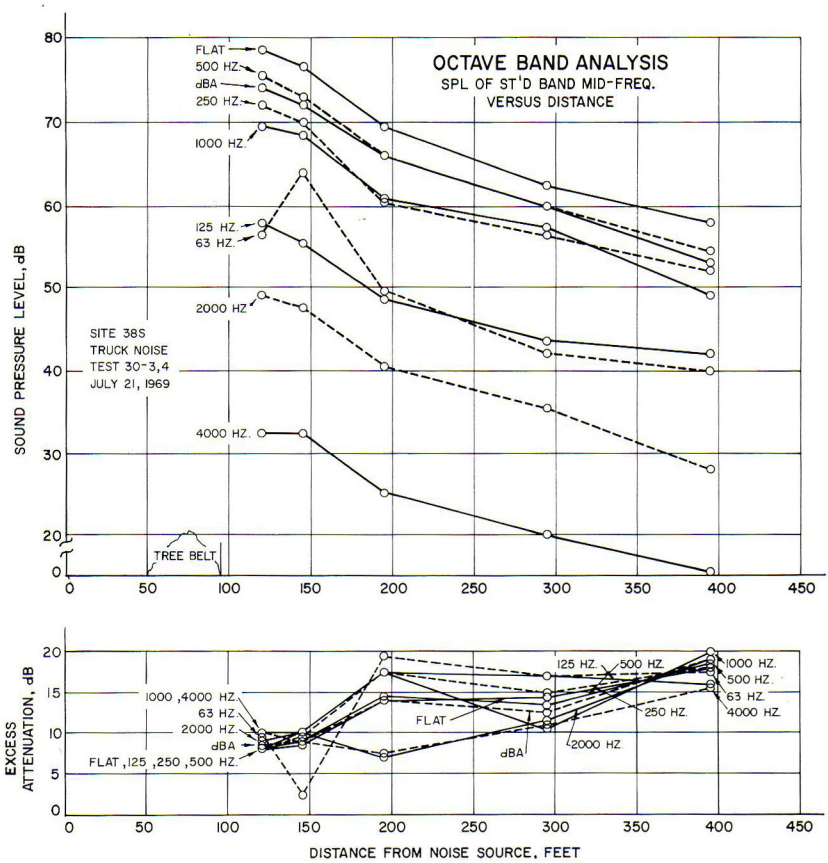

Figure 31. Site 38S, truck noise, test 30-3, 4, July 21, 1969.

Belt Location Tests

To determine the optimum placement of noise screens between a noise source and receiver, a series of tests were run at a site where surface conditions were similar on both sides of the tree belt. Sound source and microphone positions were varied simultaneously, with a corresponding variation in the relative position of the belt between source and receiver. A total transmission distance of 500 feet (source to receiver) was used, including the 90-foot-wide tree belt (Fig. 32).

A ratio R/S (receiver distance from belt/source distance from belt) was conceived as an index of tree placement. A high R/S ratio corresponds to a tree belt placed relatively close to a sound source. Results are portrayed in Fig. 33 and discussed in detail in Chapter 4 in the section "Placement of Tree Belts."

In addition to determining the optimum placement of a belt between source and receiver, it was also desired to learn how far a belt should extend on either side of a protected area for adequate noise screening A test was therefore devised in which sound level measurements were made at five selected "screen extension" distances of 0, 50, 100, 150 and 200 feet, measured from the end of the belt (Fig. 34).

The distance from noise to receiver was also varied; total transmission distances ranged from 140 to 290 feet. The results of the tests are portrayed in Figs. 35, 36 and 37 for varying source distances, measured from the front edge of the belt, of 25, 50 and 100 feet, respectively.

Urban Residential Areas

Prerecorded arterial automobile noise and urban bus noise was used in limited studies of tree-shrub combinations for noise screening in residential areas. A photograph, schematic diagram and plan view illustrate the location selected (Figs. 38 and 39).

The noise source was located 38 feet in front of the belt. The microphone was located at nine positions, 10 feet apart, behind the belt. A control test was also made along a side street with closely spaced trees and shrubs lining one side, and rather sparse plantings of tree-shrub combinations lining the other side.

For this test, as distinguished from rural area tests, the high-frequency section of the speaker system was placed near ground level, instead of on top of the low-frequency section. The objective was to simulate the position of the source of urban traffic noise, which is due primarily to tire-roadway interaction and engine exhaust. On rural highways, trucks with high exhaust stacks constitute a sizable proportion of the vehicular traffic.

Because of the different configurations of the sound projection system as used to simulate rural and urban traffic, the corresponding

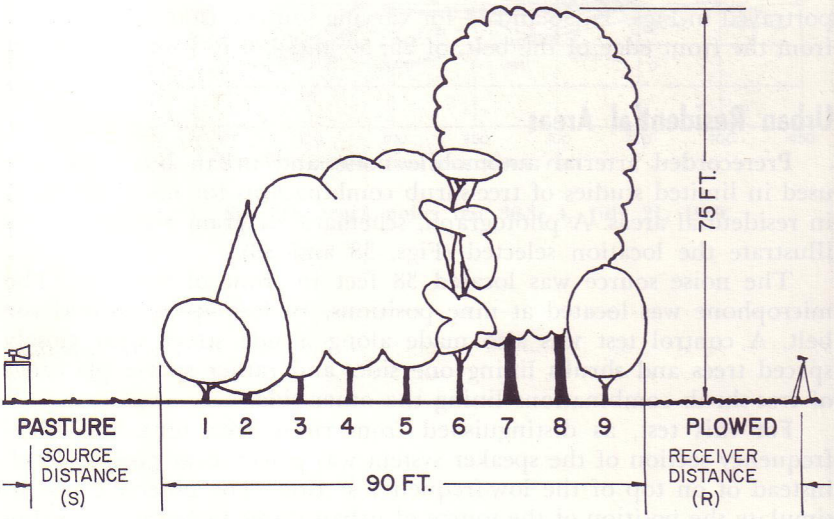

Figure 32. Belt No. 2P, George Spitz farm. Nine row belt S. to N. 75 ft. tall. 1. Russian-olive. 2. Pine and Eastern redcedar. 3. Catalpa. 4. Hackberry. 5. Hackberry. 6. Honey Locust. 7. Cottonwood. 8. Cottonwood. 9. Mulberry, Between-row spacing 10 ft.; in-row spacing 6 ft.; dense undergrowth; belt width 90 ft.

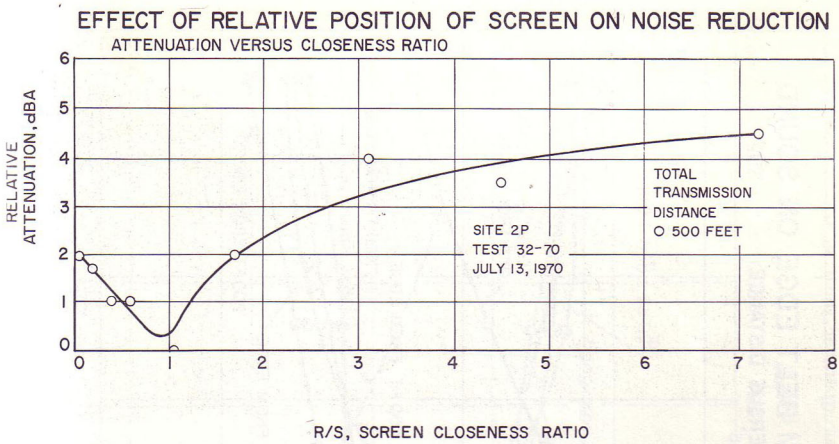

Figure 33. Effect of relative position of screen on noise reduction, site 2P, test 32-70, July 13, 1970.

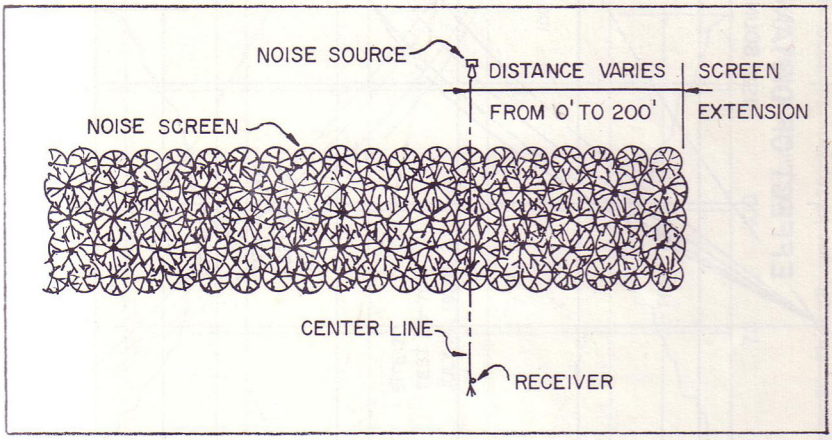

Figure 34. Sound level measurements made at five selected "screen extension" distances of 0, 50, 100, 150 and 200 ft.

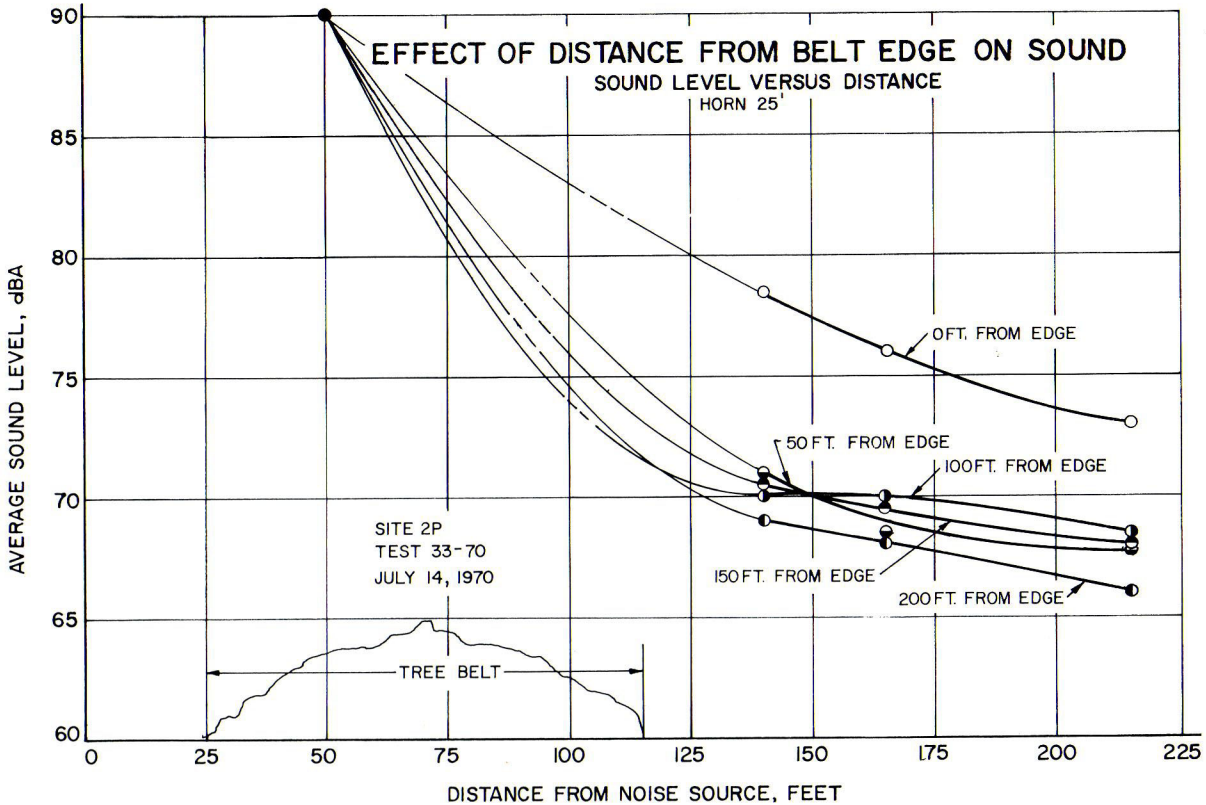

Figure 35. Site 2P, test 33-70, July 14, 1970, sound level vs. distance, horn 25 ft.

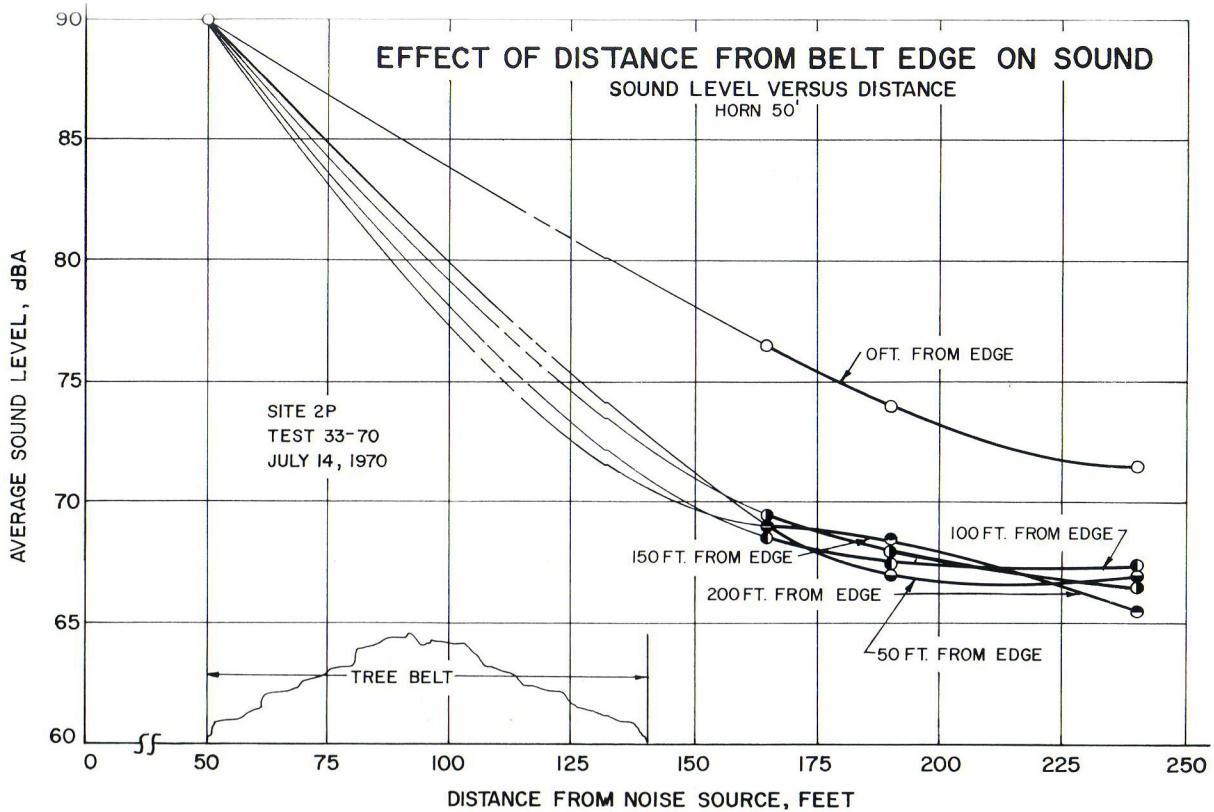

Figure 36. Site 2P, test 33-70, July 14, 1970, sound level vs. distance, horn 50 ft.

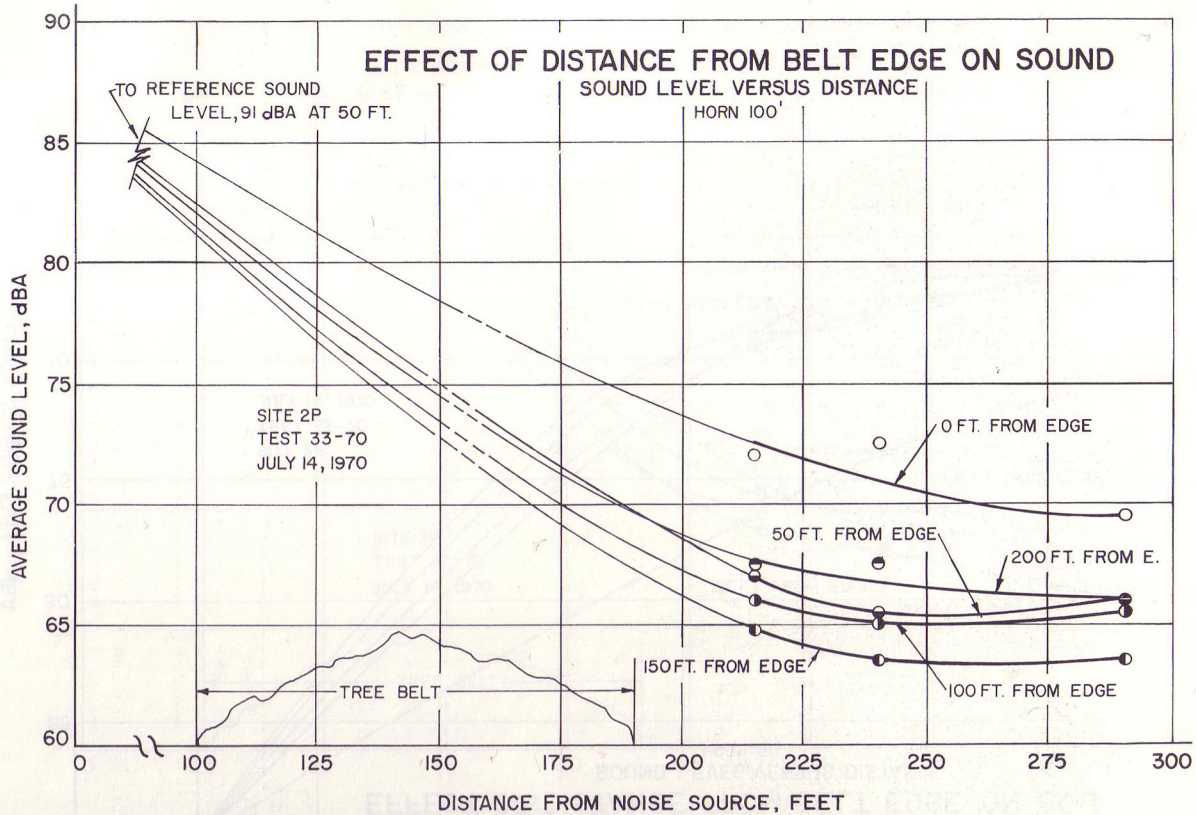

Figure 37. Site 2P, test 33-70, July 14, 1970, sound level vs. distance, horn 100 ft.

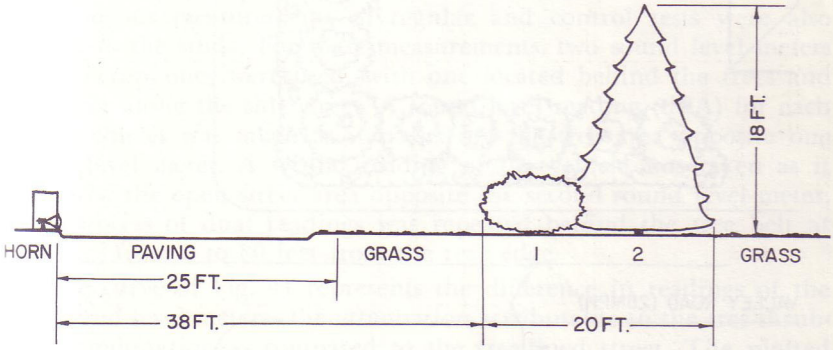

Figure 38. 56th and Valley Road. Two row belt E. to W. 18 ft. tall. 1. Cotoneaster. 2. Austrian pine. Between-row spacing 10 ft.; in-row spacing 9 ft.; in-row spacing cotoneaster 4 ft.; belt width 20 ft.

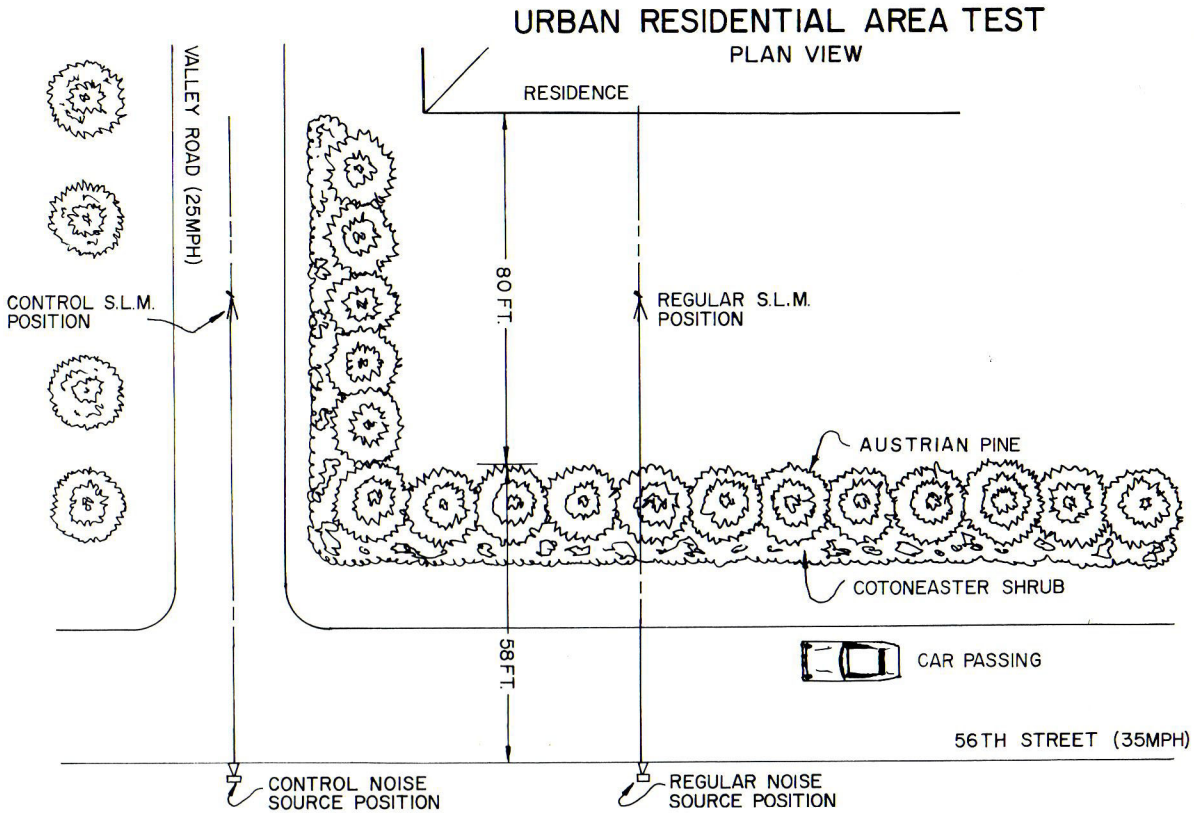

Figure 39. Urban residential area test.

noise reduction curves are not comparable. It should also be noted that the urban residential area test compares sound projection through a relatively narrow belt of trees and shrubs and over a lawn with projection over a tree-lined paved street. Some sound could be reflected from the vegetation lining the street, in addition to the reflection from the pavement, which could produce a "channel effect," accompanied by unexpectedly high sound levels.

Sound levels in the two cases are compared in the upper curves of Fig. 40. Relative attenuation attributable to the tree-shrub-grass combination when compared to the tree-lined street is illustrated by the lower curves. The exceptionally high attenuation is attributable to the lower elevation sound projection, where absorption by trees, shrubs and grass is more complete and where reflection from the pavement surface is greater; also to probable reflection from the surface presented by the trees and shrubs which lined the street.

From the preceding test results one might conclude that a straight driveway leading from a street to a residence could cause a noise problem, especially if it were bordered by hard-surfaced walls. Reflections from dense tree-shrub plantings lining the driveway could also cause some reflection of the sound. The problem might be avoided by using a curved driveway or by leaving openings in the shrubbery.

In a second type of test, unique with the urban area study, we used the actual noise of passing vehicles instead of recorded sound. Near-simultaneous measurements of regular and control tests were also unique to the study. For these measurements, two sound level meters with microphones were used, with one located behind the trees and the other along the side street. A sound level reading (dBA) for each of 10 vehicles was taken as it passed by the tree area opposite one sound level meter. A second reading of the vehicle was taken as it passed by the open street area opposite the second sound level meter. This process of dual readings was repeated behind the tree belt at distances from 0 to 80 feet from the rear edge.

The curve of Fig. 41 represents the difference in readings of the two sound level meters—the attenuation attributable to the tree-shrub-grass combination as compared to the tree-lined street. The plotted points at 128 and 138 feet are believed to be affected by reflection of the sound from the wall of the residence and were disregarded in drawing the curve.

Statistical Analysis

A multiple regression analysis of the data resulted in equations for predicting the sound level (dBA) at various distances from the noise source, including the effect of tree height, belt width, wind velocity and tree type. The equations are shown in tabular form (Table 1).

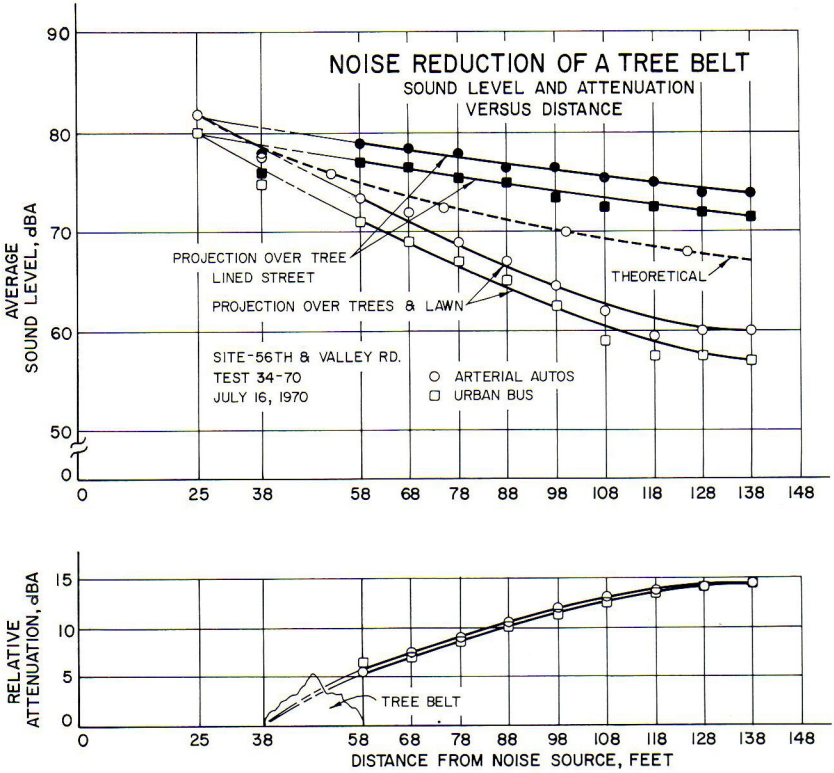

Figure 40. Site—56th and Valley Road, test 34-70, July 16, 1970.

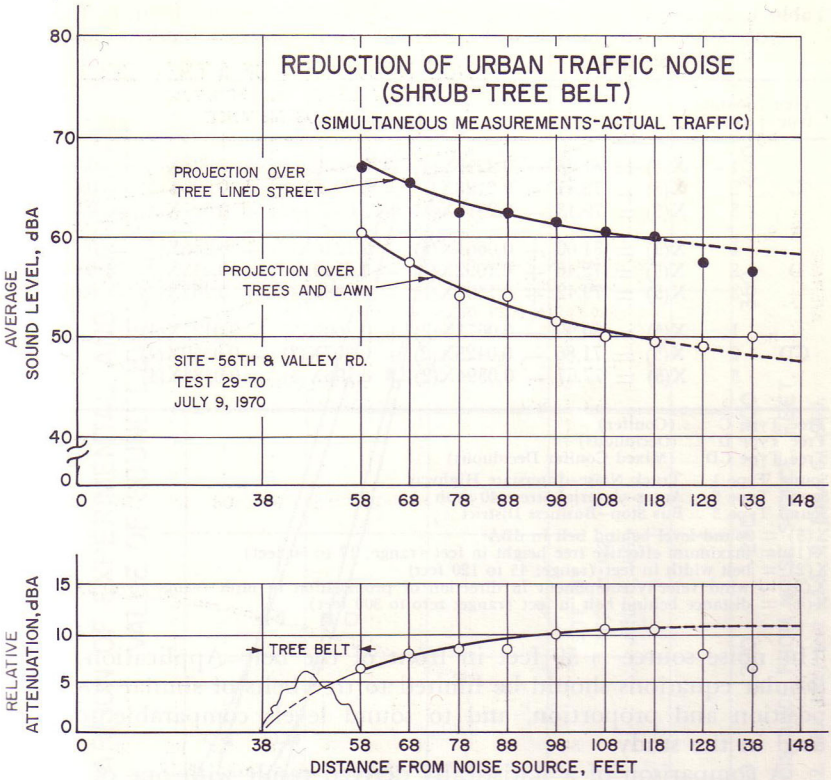

Figure 41. Site—56th and Valley Road, test 29-70, July 9, 1970.

Table 1. Equations for predicting the sound level at various distances from the noise source, including the effect of the height, belt width, wind velocity and tree type.

Tree type	Sound type	Prediction equation
C	1	$X(5) = 81.65 - 0.2257X(1) - 0.0229X(2) + 0.728X(3) - 0.0576X(4)$
	2	$X(5) = 72.91 - 0.3128X(1) + 0.0918X(2) + 0.593X(3) - 0.0544X(4)$
	3	$X(5) = 79.43 - 0.2913X(1) + 0.0665X(2) + 0.627X(3) - 0.0565X(4)$
D	1	$X(5) = 81.60 + 0.0661X(1) - 0.1246X(2) + 0.286X(3) - 0.0563X(4)$
	2	$X(5) = 72.46 + 0.1092X(1) - 0.1149X(2) + 0.253X(3) - 0.0516X(4)$
	3	$X(5) = 79.42 + 0.1599X(1) - 0.1386X(2) + 0.263X(3) - 0.0571X(4)$
CD	1	$X(5) = 80.99 - 0.0671X(2) + 0.260X(3) - 0.0427X(4)$
	2	$X(5) = 71.86 - 0.0425X(2) + 0.307X(3) - 0.0350X(4)$
	3	$X(5) = 77.67 - 0.0394X(2) + 0.196X(3) - 0.0383X(4)$

Tree Type C .....(Conifer)
Tree Type D .....(Deciduous)
Tree Type CD .....(Mixed Conifer Deciduous)

Sound Type 1 .....Truck Noise—Interstate Highway
Sound Type 2 ... Autos—Arterial Street 40 mph
Sound Type 3 ... Bus Stop—Business District

X(5) = sound level behind belt in dBA
X(1) = maximum effective tree height in feet (range: 17 to 60 feet)
X(2) = belt width in feet (range: 45 to 120 feet)
X(3) = wind velocity component in direction of propagation in mph (range: 5 to 12 mph)
X(4) = distance behind belt in feet (range: zero to 300 feet)

The noise source is 50 feet in front of the belt. Application of the tabular equations should be limited to tree belts of similar size, composition and proportion, and to sound levels comparable to those used in the study.

A comparison of a statistically derived result with one of the experimental curves is illustrated in Fig. 42. For a more complete discussion of the statistical analysis and suggested use of the equations refer to the section of Chapter IV entitled "Observations and Conclusions from the Statistical Analysis."

CHAPTER IV—OBSERVATIONS AND CONCLUSIONS

Factors Affecting Noise Reduction

Outdoor sound transmission, and therefore noise reduction, is affected by such known factors as distance; atmospheric absorption, humidity and temperature; wind gradients, speed, direction and turbulence; and by media interposed between sound source and receiver. Numerous empirical and theoretical equations have been proposed to predict the sound level at various distances from a noise source (20). One such equation, which is for a point source free sound field is:

$$S_d = S_o - 20 \log \frac{d}{d_o}$$

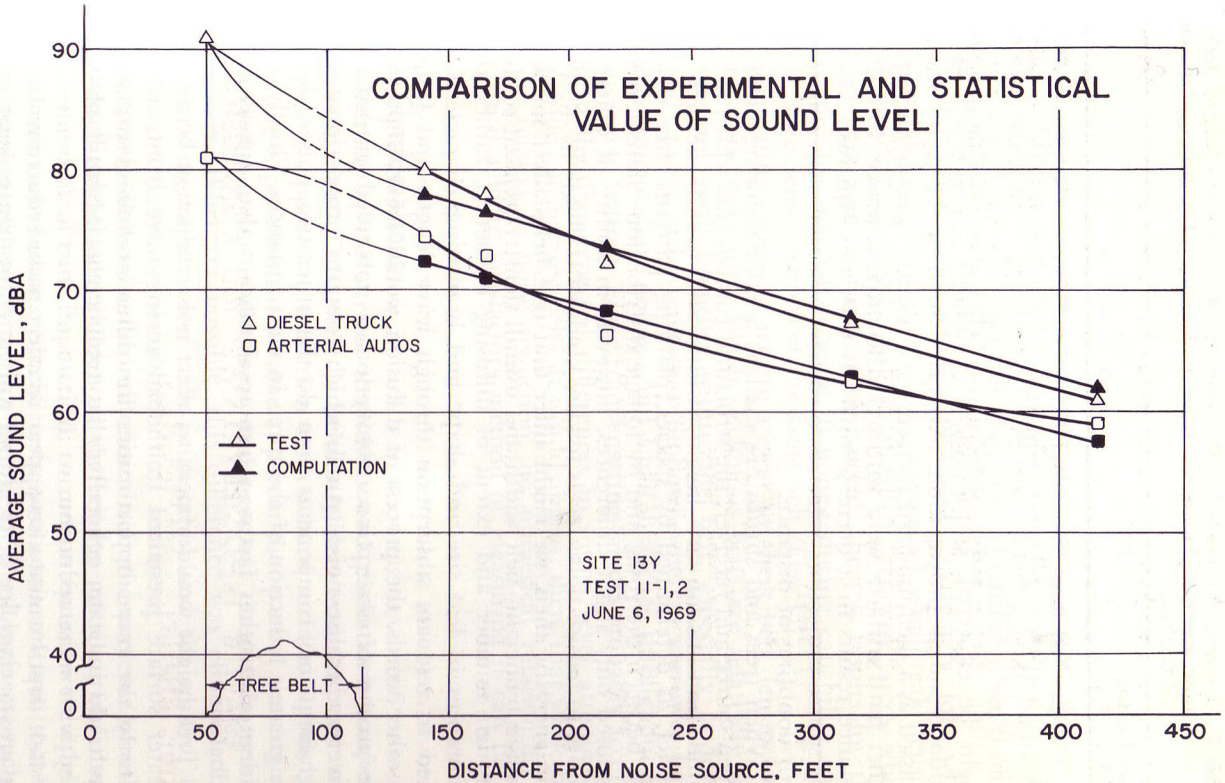

Figure 42. Site 13Y, test 11-1, 2, June 6, 1969.

where:

d = the prescribed distance from the noise source

d_0 = a reference distance where the sound level is known

S_d = the sound level (dBA) at the prescribed distance from the noise source

S_0 = the sound level (dBA) at the reference distance.

Sound levels obtained from this equation are slightly different from those measured in our study but the difference is no more than might be expected, considering the number of variables affecting outdoor sound propagation. A gravel road with grassy shoulders (classed as a medium-hard surface) gave results closest to the equation. Other hard surfaces were within 3 dBA in most cases. Doubling the distance results in a decrease of 6 dB with this equation, whereas a line source projection, referred to earlier, results in a decrease of 3 dB with doubling of distance.

When trees and shrubs are used as a noise-reducing medium between source and receiver, the structural components which may affect sound transmission are height, width and overall density of the barrier, as determined by species, planting patterns, tree spacing in and between the rows, and by foliage distribution. Statistical analysis disclosed only slight differences, however, in ability of different tree species to reduce noise levels for the kinds of traffic noise studied.

Generally, then, we might infer that tree belts affect sound transmission by height, belt width and overall density (related to diffusion through number and extent of diffusing elements), rather than by differences in leaf size and shape and branching characteristics (related to resonant absorption through wave length and frequency). In other words, the process of diffusion would seem to prevail over the process of absorption. Absorption is not ruled out completely, however, because noise type 1, which contains proportionately more high-frequency components than do the other two noises, does show the greatest reduction of the three in most instances. Finally, it seems evident that other factors are more significant than species in noise reduction.

Tree height would appear to affect noise reduction because of the greater surface presented to the advancing wave front, and consequently the more opportunities for diffusion and absorption. The results do indicate, generally, that tree height is significantly correlated with noise reduction.

Belt depth would also appear to affect noise reduction, because of the greater number of trees and consequently greater number of absorbing and diffusing elements to impede the passage of the sound. The results do indicate, generally, that belt depth is significantly correlated with noise reduction.

Belt density also undoubtedly affects noise reduction. The greater

number of elements per unit volume in a denser belt would provide a greater absorption area and more complete diffusion. A major problem arises, however, in attempting to relate belt density to noise reduction, because no completely satisfactory method has been devised for numerically measuring belt density. Estimates of the percentage of ground cover in an area have been used as a measure of density in some studies. Radioactive techniques have been devised to give a measure of the amount of matter between two points. Belt density, as understood by the windbreak specialist, refers to the ability to reduce wind velocity. In most experiments, extremely low wind velocity behind the belt indicated near-maximum windbreak density. One belt studied contained a section of rather "scrawny" trees, where passage of light was relatively unobstructed; the test results for this section showed a marked decrease in noise-reducing capability compared to more dense sections of the same belt (Fig. 43).

Compensating factors of nature appear to affect belt density and, therefore, noise reduction. Wider deciduous belts are relatively free of foliage and small branches within the belt, especially at lower levels, and appear to be somewhat "hollow" whereas narrower belts, especially conifers, have foliage and small branches throughout the belt from top to bottom. These compensating factors probably account for the smaller-than-expected differences in sound level attenuation between wide and narrow belts. It would appear, then, that while belt density is related to noise reduction, no numerical relationship is feasible until a more satisfactory method of measuring it can be devised.

Surface Considerations

The softness of the surface that the sound passes over markedly affects attenuation. This effect is primarily due to absorption of a soft surface as opposed to reflection from a hard surface. During the course of the experiments it became apparent that part of the attenuation observed was due to the trees, and part was due to the ground surface cover. Wherever possible, this difference was eliminated by making both the regular test runs (with trees) and the control test runs (without trees) over nearly identical surfaces.

When inaccessibility, unfavorable terrain or the presence of other factors which might have influenced the results, made surface duplication in the control runs impractical, correction factors were applied to the control run readings. Special tests, previously referred to, were made to develop surface correction factors for hard surfaces, such as a roadway; medium surfaces, such as short grass; or soft surfaces, such as tall grass, freshly plowed ground or tall wheat stubble.

Finally, the results indicate that the type of surface over which a sound may pass is an important consideration in any research study

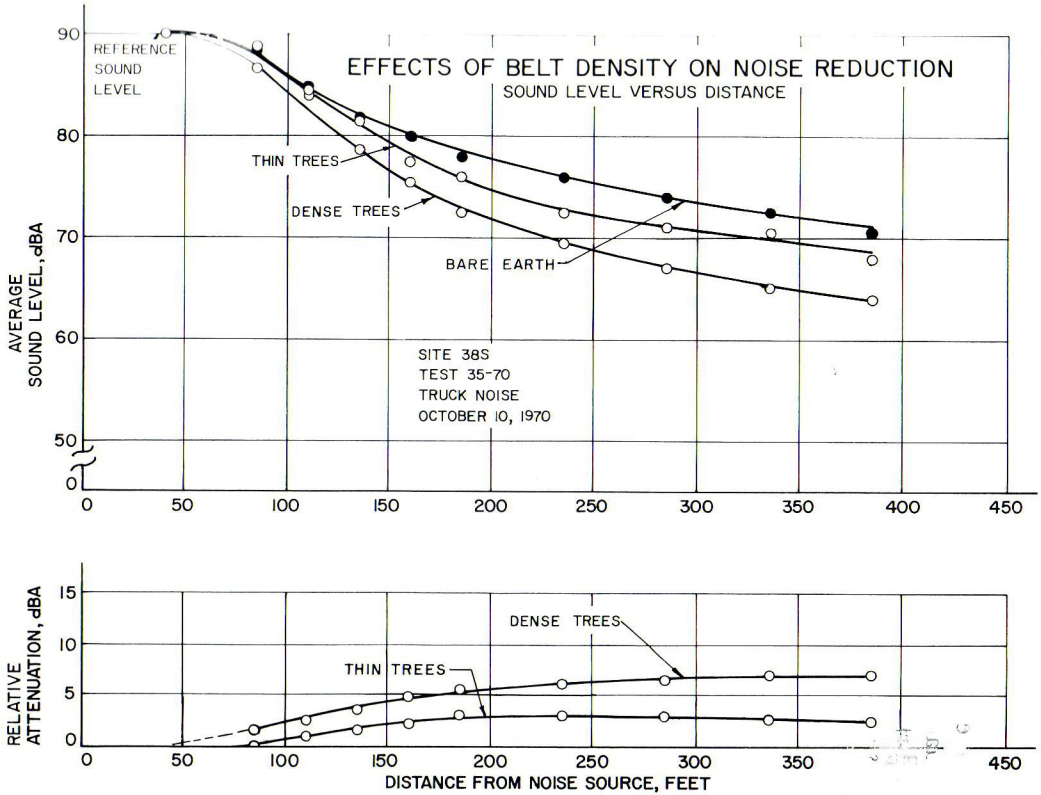

Figure 43. Site 38S, test 35-70, truck noise, October 10, 1970.

or planning operation which includes outdoor sound transmission, or noise reduction by the use of vegetation. Figs. 20, 21 and 22 in the section entitled "Comparative Surface Tests" illustrate this point. Attenuation is greatest when trees and soft surfaces are compared with hard faced pavement. *It is apparent that the presence of trees, shrubs and grass, in an area which might otherwise be hard-surfaced, would significantly reduce noise.*

Atmospheric Gradients

Atmospheric gradients of temperature, humidity and wind velocity have recognized effects on sound transmission (and noise reduction) (18). They refract or "bend" the sound rays (or wave front) upward or downward by changing the normal velocity of propagation at varying elevations. Downwind propagation, associated with a positive velocity gradient (velocity increasing with altitude) tends to bend the rays downward and maintains audibility at considerable distances. On the other hand, upwind propagation—associated with a negative velocity gradient—tends to bend rays upward and rapidly decreases audibility.

A comparable situation exists with temperature gradients during the day as the sun warms the fields. Positive temperature gradients (temperature increasing with altitude) are typical during early morning and evening hours when the ground is cool, whereas negative temperature gradients are typical during mid-days when the ground is warmed by the sun. In the summertime, a band of cooler, high-density air within a belt of trees may offer some resistance to sound penetration. This phenomenon, studied by early experimenters (1), represents another atmospheric refraction of sound associated with tree belts.

Slight variations of humidity appear to have little or no direct effect on the propagation of sound. Extremely high humidity, as during a rain or fog, however, tends to produce a more homogeneous atmosphere, and in so doing favors the propagation of sound in most cases. Humidity thus appears to have a relatively minor effect on the use of trees and shrubs for noise abatement.

The continually varying atmospheric gradients during the day and from one day to the next pose a major problem for the experimenter and contribute to variations in sound level readings which can neither be completely accounted for nor accurately compensated for. These effects can be minimized on a given day by making "tree" runs and "control" runs in immediate sequence and by adopting a standard procedure of projecting the sound for "tree" runs and "control" runs in the same direction and over similar surfaces. Test results on a given belt over a period of several days were averaged to improve

the accuracy over a single test (Figs. 3, 5, 7, 10, 12, 15 and 18 in Chapter III, Test Results).

Observations indicate that the need for downwind placement of noise screens is greater than for upwind placement, because sound level tends to decrease more rapidly upwind anyway. Further indications are that tree barriers tend to modify the wind patterns in a way which does not favor upwind sound reduction but does favor downwind reduction. Upwind placement is therefore less efficient than downwind placement.

Placement of Tree Belts

The distance from sound source to the front edge of a belt of trees or shrubs is often governed by right-of-way requirements, in the case of major highways, and by anticipated use of the space for other purposes, such as pedestrian traffic, in urban areas. Large trees closer than 50 feet from the edge of a roadway may pose a threat to auto safety. This 50-foot distance is also necessary to prevent snow from drifting over the highway, or branches from being blown onto the highway by high winds. Also, trees placed too close to highway intersections tend to decrease visibility.

Most of the tests were run at noise source distances of 50 feet from the front edge of the tree belt. For certain selected belts, tests were run at noise source distances of 25 feet. A comparison of the noise reduction curves for 25- and 50-foot source distances of the same belt disclosed only minor differences in attenuation. Any advantage gained by placing the belt much closer than 50 feet to the noise source appears to be offset by other factors.

Results of the belt location tests, to determine optimum placement of large tree belts between a noise source and an area to be protected, were portrayed in Fig. 33. The curve on the graph shows a pronounced "dip" at an R/S ratio (receiver to source distance) equal to unity. This corresponds to a tree belt placement midway between noise source and receiver and indicates low attenuation and ineffective placement of the belt. The attenuation increases as the R/S ratio increases, indicating a more effective placement of the belt. The upward turn of the curve at low R/S values, which correspond to a placement of a belt close to a protected area, indicates that some benefit may be realized by having the belt "close in" but not as much as when the belt is placed near the noise source.

The curve does not represent a sufficient number of tests to justify its use for design purposes but does support earlier observations that trees most efficiently screen noise when they are placed relatively close to the noise source, providing the foliage extends to the ground. There is a possibility of "blast through" of high intensity sound at ground level and at the closer source distances, where the wave front

is more concentrated, and where there are openings in the tree structure and foliage pattern. This effect may be partially responsible for inconsistencies found when 25 foot and 50 foot source distance test results are compared. *It would seem that planting distances from 35 to 65 feet from the noise source would yield optimum results for tree belts of considerable height and depth in rural areas.*

Other tests within the city indicate that placing trees and shrubs close to a noise source is desirable; a distance of 10 to 25 feet from a noise source to nearest shrub would seem to yield optimum results.

Results of the second type of belt location tests, to determine the desirable extent of a noise screen on either side of a protected area, were portrayed in Figs. 35, 36 and 37. Similar results were observed with "in-town" tests. For good results, the noise screen should extend on both sides of a protected area for approximately the distance from noise source to receiver. The screen should hide the noise source from view, until the distance from source to receiver is sufficient to produce an acceptably low noise level without the benefit of the noise screen.

Acceptable Noise Levels

Acceptable noise levels differ greatly, depending on environmental surroundings, personal preferences and practical necessity. Various criteria have been proposed, from time to time, for acceptable noise levels (5) and several methods have been devised for rating them. One such method is based on a so-called "Speech Interference Level" (SIL). The speech interference level of a noise is the arithmetic average, in decibels, of the sound pressure levels of the noise in the three standard octave bands having center frequencies of 500, 1,000 and 2,000 Hz (cycles per second). Speech interference levels below 60 dB will permit normal conversation at a distance of 3 feet but the voice must be raised mederately at a distance of 6 feet.

A second method (6) is based on a set of numbered noise rating curves, which emphasize the greater sensitivity of the ear to higher frequencies. The noise is first analyzed in octave band widths, then the decibel level of each band is plotted on the curves, to give the octave band spectrum. A noise rating number "N" is picked from the curve which lies just above the octave band spectrum. This number is then corrected by reference to tables to adjust to specific circumstances.

Other criteria for acceptable noise levels have been determined by personal interview surveys to meet special requirements. One such study (20) has indicated a traffic noise level of about 68 dBA to be the dividing line between "disturbing" or "not disturbing," as perceived by the majority of homeowners.

Persons accustomed to living and working in relatively quiet surroundings would undoubtedly consider 68 dBA to be unacceptable. Speech interference levels below 50 dB (corresponding to about

57 dBA) are generally considered desirable for residential districts, especially during the evening hours. We believe that the speech interference level, because of its ease of interpretation, is preferable to other more complex criteria for use in the present study.

The dBA unit, which is by far the easiest to apply, is favored by many engineers for the measurement of broad band noises, such as traffic noises; the Department of Housing and Urban Development has recently adopted this unit for specifying adequate housing noise level criteria. The dBA unit, when used with adequate knowledge of its significance and limitations, will probably be quite satisfactory for most practical applications.

The relationship between sound measurement units of dBA, dB(FLAT) and SIL for the traffic noises studied (Table 2) is included for reference and application in solving illustrative problems in Appendix B.

Value of Trees as Noise Screens

The value of trees as noise screens is affected by proper placement, sufficient density and adequate tree height and belt width for each particular application. A relatively narrow belt of dense shrubs and moderately tall trees, which would be adequate for noise screening in urban residential areas, might be ineffective in rural areas where large trucks and buses were the principal noise source.

Numerical values indicating the effectiveness of trees as noise screens in a wide variety of situations may be read from the various curves in Chapter III. Sound level reductions from 5 to 8 decibels (dBA) are common for wide belts of trees. Reductions of 10 dBA are not unusual.

The subjective nature of sound complicates the process of assessing the apparent reduction in loudness based on a numerical measure, especially to one unfamiliar with acoustical terminology and measurements. Extensive experiments on individuals have indicated a reduction of 10 decibels to be approximately "half as loud." The 5 to 8 dBA reduction would, in many instances, reduce the noise level from "disturbing" to "not disturbing," particularly in the critical range of 65 to 70 dBA, where speech interference begins.

Table 2. Traffic noise level conversions, SIL, dBA, dB(FLAT).

Noise type 1			Noise type 2			Noise type 3		
SIL	dBA	dB FLAT	SIL	dBA	dB FLAT	SIL	dBA	dB FLAT
43	50	53	45	50	56	45	50	53
53	60	63	54	60	65	55	60	65
62	70	72	66	70	76	65	70	73
73	80	83	75	80	86	75	80	83
83	90	94	84	90	96	84	90	92

Special surface conditions, previously described, are an integral part of the evaluation. When "soft" tree-shrub-grass combinations are compared to "hard" pavement surfaces, the reduction is considerably greater, often in the 8 to 12 dBA range and occasionally as high as 15 dBA, or approximately one-third as loud.

It is apparent that the value of trees as noise screens depends somewhat on the type of surface over which the sound passes, and that precise separation of the combined effects of trees and accompanying soft ground cover is not an easy matter. Wide belts of trees are seldom found in the center of large paved areas. Nevertheless, attenuations from 8 to 12 dBA can be attained by the use of trees alone, compared with sound projected over a hard surface.

The present study did not involve testing of specific trees and shrubs for their effectiveness in reducing noise. Based on a knowledge of tree and shrub characteristics and on results obtained with species in the plantings tested in this study, however, we have listed evergreen trees and shrubs that should be suitable for year-round noise screening and that have a relatively wide range of adaptability (Table 3).

Additional trees and shrubs may be selected (34, 35, 36, 37 and 38). Before selecting materials, however, consult with local nurserymen, extension horticulturists and landscape architects for specific varieties and combinations of plant materials to be used in a given locality.

Limitations on the Use of Trees and Shrubs as Noise Screens

The physical nature of sound and the extreme sensitivity of the human hearing mechanism restrict the ability of trees and shrubs to reduce noise. Total elimination of sound would require that a noise source be sealed off by an airtight enclosure. Although the loudness of a sound may be reduced, it can seldom be brought below the threshold of hearing. Thus any form of natural vegetation, no matter how extensive, is incapable of "eliminating" all sound; we must concern ourselves with how much or what part of a noise can be eliminated.

Practical considerations often limit the use of trees and shrubs as noise screens. It has been mentioned earlier that it is more desirable to place trees close to a noise source as opposed to close to a receiver, and that belts of 75 to 100 foot width are desirable. Therefore, right-of-way or land use requirements may prevent effective noise screening.

Ground forms frequently limit the use of trees as noise screens. Where traffic on elevated highways is visible over the tops of the trees for example, the sound merely passes over the trees, with relatively minor absorption from below.

Natural causes also limit the effectiveness of trees in noise reduction. Very thinly planted trees, or trees in poor condition due to

Table 3. Evergreen trees and shrubs that should be suitable for year-round noise screening and that have a relatively wide range of adaptability.

Common name[a]	Regions of best adaptability
Tall	
Fir	
white	Nationwide
Veitch's silver, Nikko	East
balsam	Midwest, North, Northeast
corkbark	Midwest, Southwest, Southeast
Fraser	East, Southeast
California red	West
Spanish	West Coast
Cedar	
atlas	West Coast
deodar, Cedar of Lebanon	West Coast, South, Gulf Coast
Port-Orford cedar	West Coast, South, Southeast
Arizona cypress	Southwest, South, Southeast
Spruce	
Norway, white Serbian,	Nationwide (best in north)
Oriental, blue	Nationwide (best in north)
Pine	
western white	West
ponderosa	West, Midwest
Scotch	Nationwide (best in north)
red	East, North
Austrian, eastern white	Midwest, East
Monterey	California Coast
Douglas fir	Nationwide (except South)
Giant sequoia, Redwood	West Coast
Western redcedar	West
Hemlock	
eastern	East, Southeast
Carolina	East Coast, Southeast, South
western	West Coast
Medium	
Juniper (upright)	
eastern redcedar and varieties	East of Rocky Mountains
Rocky Mountain and varieties	West of Rocky Mountains, Midwest
Chinese and varieties	Nationwide
Grecian	Nationwide
Irish	Nationwide (best in north)
Swedish	Nationwide (best in north)
Yew	
Japanese and varieties	Nationwide
English	Nationwide (best in east)
Arborvitae	
American and varieties	Nationwide (best in north, northeast)
Oriental and varieties	South
Short	
Juniper	
Chinese (Pfitzer) and others	Nationwide
Mugo pine	Nationwide

Table 3 (Continued).

Common name[a]	Regions of best adaptability
Arborvitae	
American and varieties	Nationwide
Oriental and varieties	Nationwide
Yew	
Japanese and varieties	Nationwide
Some Broad-leaved Evergreens	
Pyracantha	Nationwide (best in south half)
Euonymus	Nationwide
Privet	South

[a] See Appendix C for scientific nomenclature

neglect or unfavorable growth environment, offer little resistance to the passage of sound, even though they serve as a partial visual screen. This effect is illustrated in Fig. 43 where the reduction of noise level by a section of a belt in good condition (dense trees) is compared with a section of the same belt in rather poor condition (thin trees).

Although the limitations are formidable, trees and shrubs can effectively reduce noise levels in many applications. They are not applicable in all situations, however; a knowledge of out-of-door sound propagation, aided by experience, is necessary to make valid judgments on the use of trees and shrubs for noise reduction.

Observations and Conclusions from the Statistical Analysis

One purpose of a multiple regression analysis is to examine the relationship among a single criterion (dependent) variable and two or more predictor (independent) variables. In this case the sound level is the criterion and tree height, belt width, wind velocity and distance behind belt are predictor variables. The analysis provides a test as to whether the independent variables can significantly predict the value of the dependent variable and, if they can, the analysis also provides an equation for predicting the unknown dependent value from a new set of independent values.

In the mathematical process a summary statistic called the multiple correlation coefficient (R) is usually computed. The coefficient provides an estimate of the proportion of the total variance in the dependent variable that can be predicted from the known variance in the independent variables, and is a measure of the overall effectiveness of the multiple regression. The standard error of estimate of a regressed score is also computed, as in an F test of the statistical significance of R. This latter statistic indicates whether the independent variables utilized have enough explanatory power to statistically predict the dependent variable.

Details of the computational method are well known to statisticians and are, therefore, omitted from the discussion. The order of entry

Table 4. Order of entry of variables in the analysis.

Tree type	Sound type	Variables analyzed and sequence of entry			
		First entry	Second entry	Third entry	Fourth entry
D	1 (Truck)	X(4)	X(2)	X(3)	X(1)
	2 (Autos)	X(4)	X(2)	X(3)	X(1)
	3 (Bus Stop)	X(4)	X(2)	X(3)	X(1)
CD	1 (Truck)	X(4)	X(2)	X(3)	.....
	2 (Autos)	X(4)	X(2)	X(3)	.....
	3 (Bus Stop)	X(4)	X(2)	X(3)	.....
C	1 (Truck)	X(4)	X(1)	X(3)	X(2)
	2 (Autos)	X(4)	X(1)	X(3)	X(2)
	3 (Bus Stop)	X(4)	X(1)	X(3)	X(2)

Tree Type D (Deciduous)
Tree Type CD (Mixed Conifer Deciduous)
Tree Type C (Conifer)
X(1) = tree height (Range: 17 to 60 feet)
X(2) = belt width (Range: 45 to 120 feet)
X(3) = wind speed (Range: −5 to +12 mph)
X(4) = distance from rear edge of belt to observer (Range: zero to 300 feet)

of the variables in the analysis has been included in Table 4 for the benefit of those persons who may wish to examine the statistical significance of the test results. One might conclude from the analysis that, in most instances, all variables considered do affect the result.

The prediction equations listed in Chapter III (Table 1) were based on assumed linear relationships, for simplification, and are not expected to give precise values. Numerical results derived from the equations varied up to 5 dBA from the experimental values, at 200 and 300 foot distances behind the tree belt. Examination of the equations also discloses differences of sign on certain terms, which, when considered independently, would give inconsistent results under certain maximizing conditions. For these reasons the equations should not be applied to belts differing in size, composition and proportion from those used in the study.

Also, the constant term of the equations implies that they are limited in application to projected sound levels used in the experiments. It is therefore recommended that they be used for first approximations and that equations for sound type 1 (truck noise), which was studied more extensively, be used in preference to the other two. The use of the experimental "tree curves" found in Chaptr III is preferred when accurate results are desired.

CHAPTER V—RECOMMENDATIONS

Current Applications

1. To reduce noise from high-speed car and truck traffic in rural areas, plant 65- to 100-foot-wide belts of trees and shrubs, with the edge of the belt within 50 to 80 feet of the center of the nearest traffic lane. Center tree rows should be at least 45 feet tall (See Table 3 for species recommendations). Where right-of-way width is large, as on certain sections of Interstate highways, several rows of trees and shrubs may be planted, to reduce noise levels at adjacent property.

2. To reduce noise from moderate-speed car traffic in urban areas, where tire-roadway interaction is the principal cause of noise, plant 20- to 50-foot-wide belts of trees and shrubs, with the edge of the belt from 20 to 50 feet from the center of the nearest traffic lane. Use shrubs 6 to 8 feet tall next to the traffic lane, with backup rows of trees 15 to 30 feet tall (see Table 3 for species recommendations).

3. Trees and shrubs should be planted close to the noise source, as opposed to close to the protected area, for optimum results.

4. Where possible, use taller varieties of trees which have dense foliage and relatively uniform vertical foliage distribution (or combinations of shorter shrubs and taller trees to give this effect). Where the use of tall trees is restricted, use combinations of shorter shrubs and tall grass or similar soft ground cover, as opposed to paving, crushed rock or gravel surfaces.

5. Trees and shrubs should be planted as close together as practical, to form a continuous, dense barrier. The spacing should conform to established local practices for each species.

6. Where year-round noise screening is desired, evergreens, or deciduous varieties which retain their leaves throughout most of the year, are recommended.

7. The belt should be approximately twice as long as the distance from the noise source to the receiver and when used as a noise screen parallel to a roadway, should extend equal distances along the roadway on both sides of the protected area.

8. During daytime at recreational sites and other rural areas where small groups might wish to converse normally, the speech interference level (SIL) should be held to 55 to 60 dB, which corresponds to approximately 62 to 68 dBA. An SIL of 40 to 48 dB, corresponding to approximately 47 to 55 dBA, is recommended during night hours.

9. During the day in residential areas an SIL of 48 to 53 dB, corresponding approximately to 55 to 60 dBA, is desirable although

values up to 65 dBA might be tolerated for short periods of time. An SIL of 43 to 50 dB, corresponding approximately to 50 to 57 dBA, is recommended during evening hours.

Future Study

1. Long-term studies, using plantings specifically designed for noise screening, where tree species and ground surface characteristics could be under direct control of the experimenter, offer the best opportunity for developing the full potential of trees and shrubs as noise screens. Property must be available for a period of several years for this purpose.

2. Studies with an objective of finding short-term solutions to the noise problem. This might involve combinations of trees, shrubs, ground cover and land forms, or other solid barriers, and could result in recommendations for almost immediate partial relief, with later permanent solution to the noise problem as the trees matured.

3. Studies for limited distance noise screening, where distance from noise source to protected area is small, as in the case of urban property, and where wide belts of trees are not feasible.

4. Extended studies of trees, shrubs and other vegetation in their ability to absorb sound, when compared to propagation over hard surfaces, such as pavement and bare earth.

APPENDIX A

Glossary of Technical Terms

Attenuation — A reduction in value, often applied to measurements of sound and electricity.

Decibel (abbreviated dB) — A logarithmic unit which indicates the ratio between two quantities, commonly electrical or sound energy levels or pressure levels. (See Sound Pressure Level.)

dBA — A "weighted" measure of sound pressure level which provides relatively high correlation with subjective estimates of loudness of certain noises. (See Sound Level.)

Free Sound Field — A field in a uniform medium surrounding a sound source, which is relatively free from boundary effects (echo, etc.).

Frequency — The time rate of repetition of a periodic phenomenon, having units of cycles per second (Hz). In sound control measurements variations of air pressure from 20 Hz to 15,000 Hz adequately represent the audible range.

Level — A physical measurement of a quantity referred to a similar reference quantity (usually lower in value). In acoustics, sound power level and sound pressure level are the usual levels encountered.

Loudness — The intensive attribute of an auditory sensation; a subjective quantity, dependent on frequency and pressure, and ranging from soft to loud. (See Sone and Phon.)

Microbar — A unit of pressure equal to 1 millionth of the standard atmospheric pressure, also equal to one dyne per square centimeter.

Noise — Any unwanted sound, usually an erratic random oscillation, also applied to electric waves.

Noise Level — A degradation of sound level, used where disagreeable sound (noise) is being considered.

Octave — An interval between two pure tones or oscillations having a frequency ratio of two.

Octave Band — Segment of the audio spectrum having a width of one octave. For convenience of analysis ten standard octave bands having geometric mean frequencies of 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, 16,000 Hz are often used.

Phon — The unit of loudness level. (See Loudness, Level)

Sone — The unit of loudness — One sone corresponds to a 1,000 Hz tone of 40 dB intensity. Any sound that is judged to be n times that of this one-sone tone is n sones. Sones are related to Phons through the expression

$$S = 2^{(P-40)/10}$$

Sound — An oscillation in pressure, particle displacement, velocity, etc., in an elastic medium capable of affecting the hearing mechanism, in the ordinary sense.

Sound Level — A weighted sound pressure level obtained by tailoring the response characteristics of Sound Level Meters to meet certain criteria, for example: dBA is the A-scale weighted sound pressure level, and dBC is the C-scale weighted sound pressure level (essentially flat or uncorrected in the audio range). Scale characteristics are specified by the American Standards Association.

Sound Pressure Level (SPL) — A measure of the rms sound pressure relative to an arbitrary reference pressure approximating the threshold of hearing. Definition by equation is

$$SPL = 20 \log (P/P_0) \text{ (decibels)}$$

where P_0 = reference sound pressure of 0.0002 dynes per sq cm (microbars)

P = measured sound pressure

Speech Interference Level (SIL) — The average, in decibels, of the sound pressure levels in the octave bands which contain most of the speech frequencies, i.e., the 500, 1000 and 2000 Hz unit frequency bands.

Concepts Relating the Decibel to the Physical Senses

The audible range of sound pressures extends from approximately zero decibels at the threshold of audibility to 130 decibels at the threshold of feeling.

The majority of ordinary sounds we hear fall in the range of about 25 decibels (a quiet library) to about 80 decibels (a very noisy street corner).

A difference of one decibel is the smallest change in loudness which can be easily detected by the ear.

An increase of 10 decibels corresponds to approximately doubling the apparent loudness of a sound for most of the audible range.

APPENDIX B

Illustrative Solved Problems

Five solved problems are offered to illustrate how the material in this publication may be used in a practical manner. The examples are by no means comprehensive, as many other applications are likely to be found.

The first two problems are hypothetical but represent situations which are likely to occur frequently. The last three are simplifications of actual problems.

Problem 1

A moderate-cost housing development is to be built adjacent to a freeway, on level terrain; trees and shrubs are needed as a protective noise screen. A clear space of at least 100 feet between house and trees is desired. Where should the trees be placed, what species should be used and what width belt is necessary to provide optimum results?

Analysis and Solution: An acceptable noise level is based on the speech interference level (SIL) and recommendations in Chapter V. A level of 50 SIL is suggested as a compromise between maximum daytime and minimum nighttime levels for the type of housing planned. Referring to the "SIL" chart (Table 2) this corresponds to a level of 57 dBA for trucks, which are likely to constitute the major part of the noise disturbance. Reference to several graphs (Figs. 3, 7 and 18) indicates that a 450-foot distance between highway and residence is necessary to achieve the desired result. Assuming the belt is 50 feet from the freeway and that a 100-foot-wide planting is selected, the clear space of 100 feet between house and trees would be readily available.

An alternate solution is also offered. Based on a demonstrated attenuation of 5 to 8 dBA per 100 feet of belt width, a 200-foot-wide belt could be planted. Then, reference to the graphs shows that the houses could be located approximately 350 feet from the highway, a saving of 100 feet. The species selected should be mainly evergreens. However, since outdoor activity would likely be decreased in the winter, a mixture of deciduous and evergreen trees would be satisfactory, with the evergreens being planted on the front and back of the belt and the deciduous trees toward the center. Spacing of the trees should be as close as practical but conforming to local recommendations.

Problem 2

An outdoor recreational site and picnic area is to be established adjacent to a major highway, where large trucks are a significant part of the traffic. A tree planting must be designed to provide noise protection satisfactory for daytime use. How close to the highway may the site be placed and where in relation to the highway should the noise screen be located?

Analysis and Solution: An acceptable noise level based on recommendations in Chapter V for daytime recreational areas is 55 to 60 SIL. A level of 57 (SIL) is suggested for the type of activity anticipated. Referring to the "SIL Chart" (Table 2) the corresponding level is 65 dBA. Reference to several graphs (Figs. 10, 12 and 15) indicates that locating the site 250 to 300 feet from the noise source would provide the desired results. A distance for the tree planting of 50 feet from

the highway is chosen as most efficient and within acceptable safety standards. A mixture of evergreens and deciduous trees is suggested for the site, since its principal use will be during months of the year when deciduous trees have foliage. Dense plantings are also recommended in accordance with accepted local standards for tree spacing.

Problem 3

Heavy arterial traffic has caused considerable disturbance at a residential property, especially in the back yard area, which is adjacent to the street. What type and location of plantings are recommended to serve as a noise screen?

Analysis and Solution: Since the noise is largely due to tire-roadway interaction on passenger cars, with no large truck traffic, a relatively narrow belt of shrubs and trees of medium height should considerably reduce the noise level. A row of dense shrubs—juniper or cotoneaster—backed up by one or two rows of 10- to 15-foot-high evergreens and a third row of fast-growing poplars or cottonwoods will make a belt with a total depth of 20 to 30 feet at maturity. The nearest planting should be within 50 feet of the street. Reference to Fig. 40 indicates a level of 60 to 65 dBA (corresponding to 53 to 57 SIL) can be attained at a distance of 50 feet behind the belt. Although this value is higher than recommended for ideal conditions (below 50 SIL for outdoor residential levels) the situation is severe and not a great deal more can be accomplished.

Problem 4

This problem illustrates the *increase* in noise level accompanying the removal of a belt of trees.

A highway widening project has eliminated a wide belt of trees adjacent to a small animal farm. The project also changed the ground configuration and increased traffic speed and noise. Because the animals are quite sensitive to noise, their productivity decreased. What can be done to reduce the noise level at the animal houses?

Analysis and Solution: Construction of new housing for the animals was suggested. The location recommended was based on the probable increase of the sound level due to the removal of 70 feet of dense plantings of large deciduous trees and a 15 m.p.h. increase in speed limit, plus a slight amount for ground form changes. From the graph of Fig. 7 for a belt of comparable size, a 5 to 8 dBA attenuation was indicated. Adding 2 to 4 dBA for the increased speed limit (determined by a separate test) and the ground form change, the probable increase was placed at 7 to 12 dBA. Referring to the upper curves on this same graph it is seen that, in the 200-400 foot range, a 150- to 250-foot distance is required to offset this increase. It was

therefore recommended that the animal houses be moved 200 feet farther from the highway.

Problem 5

A truck stop established within 800 to 1,000 feet of a residential area caused an increase in the noise level. What steps are recommended to reduce the noise level with trees and shrubs?

Analysis and Solution: The sound level at this distance is probably relatively low the majority of the time but could become annoying during evening hours, when background levels are lower and atmospheric conditions favor transmission of sound. The recommended solution is to plant a 75-foot-wide belt of trees between the residential area and the truck stop, with the trees as close as possible to the truck stop.

Evergreens of a species suited to the locality should be planted, with minimum spacing recommended for the species selected. Maintain a soft ground cover of taller grasses or other vegetation between the truck stop and residential area. For an immediate solution, a temporary solid wall high enough to completely screen the trucks from view appears to be the only possibility. The wall, to be most effective, should be close to the noise source, and could be removed when the trees had reached a height of 15 to 20 feet.

Fig. 7 indicates that an excess attenuation of approximately 7.5 dBA is attainable at a 400-foot distance and that this attenuation shows no tendency to decrease at greater distances.

Expected results would be a substantial decrease in the noise level except during occasional periods of unfavorable atmospheric conditions. The noise would still be audible outdoors the majority of the time, however, because of its high intensity, but should not be objectionable to most persons.

APPENDIX C

Common and Scientific Names of Plants Mentioned

Apricot	*Prunus armeniaca* L.
Arborvitae, American (northern white cedar)[a]	*Thuja occidentalis* L.
Arborvitae, oriental[a]	*Thuja orientalis* L.
Ash, green	*Fraxinus pennsylvanica* Marsh.
Catalpa, northern	*Catalpa speciosa* Warder
Cedar, atlas	*Cedrus atlantica* Manetti
Cedar, deodar	*Cedrus deodara* (Roxburgh) Loudon

Cedar, of Lebanon	*Cedrus libani* Loudon
Cedar, Japanese	*Cryptomeria japonica* (Linneaus fil.) Don.
Cedar, Port-Orford	*Chamaecyparis lawsoniana* (A. Murr.) Parl.
Cottonwood, plains	*Populus deltoides* var. *occidentalis* Rydb.
Cotoneaster	*Cotoneaster* sp. B. ehrh.
Cypress, Arizona	*Cupressus arizonica* Greene
Douglas fir	*Pseudotsuga menziesii* (Mirb.) Franco
Elm, American	*Ulmus americana* L.
Elm, Siberian	*Ulmus pumila* L.
Euonymus	*Euonymus* sp. L.
Fir, balsam	*Abies balsamea* (L.) Mill.
Fir, California red	*Abies magnifica* A. Murr.
Fir, corkbark	*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.
Fir, Fraser	*Abies fraseri* (Pursh) Poir.
Fir, Nikko	*Abies homolepsis* Siebold & Zuccarini
Fir, Spanish	*Abies pinsapo* Boissier
Fir, Veitch's silver	*Abies veitchii* Lindley
Fir, white	*Abies concolor* (Gord. & Glend.) Lindl.
Hackberry	*Celtis occidentalis* L.
Hemlock, Carolina	*Tsuga caroliniana* Engelm.
Hemlock, eastern	*Tsuga canadensis* (L.) Carr.
Hemlock, western	*Tsuga heterophylla* (Raf.) Sarg.
Honey locust	*Gleditsia triacanthos* L.
Juniper, Chinese[a]	*Juniperus chinensis* L.
Juniper, eastern (redcedar)[a]	*Juniperus virginiana* L.
Juniper, Grecian	*Juniperus excelsa* Bieberstein
Juniper, Irish	*Juniperus communis* var. *hibernica* (Loddiges) Gordon
Juniper, Rocky Mountain[a]	*Juniperus scopulorum* Sarg.
Juniper, Swedish	*Juniperus communis* var. *suecica* Aiton.
Mulberry	*Morus alba* var. *tatarica* Loud.
Pine, Austrian	*Pinus nigra* Arnold
Pine, eastern white	*Pinus strobus* L.
Pine, Monterey	*Pinus radiata* D. Don
Pine, mugo (Swiss mountain)	*Pinus mugo* Turra
Pine, ponderosa	*Pinus ponderosa* Laws.
Pine, red	*Pinus resinosa* Ait.
Pine, Scotch	*Pinus sylvestris* L.
Pine, western white	*Pinus monticola* Dougl.

Privet	*Ligustrum* sp. L.
Pyracantha (Firethorn)	*Pyracantha coccinea* Roem.
Redcedar, western	*Thuja plicata* Donn.
Redwood	*Sequoia sempervirens* (D. Don) Endl.
Russian-olive	*Elaeagnus angustifolia* L.
Sequoia, giant	*Sequoiadendron giganteum* (Lindl.) Buchholz
Spruce, blue (Colorado)	*Picea pungens* Engelm.
Spruce, Norway	*Picea abies* (L.) Karst.
Spruce, Oriental	*Picea orientalis* (L.) Carriere
Spruce, Serbian	*Picea omorika* (Panocie) Bolle.
Spruce, white	*Picea glauca* (Moench) Voss
Yew, English[a]	*Taxus baccata* L.
Yew, Japanese[a]	*Taxus cuspidata* Siebold & Zuccarini

[a] The type and horticultural varieties and cultivars.

APPENDIX D

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