

FINAL REPORT

Acoustics of Sound Transmission Over Noise Barrier Walls

Project III-H2, FY 97

Report No. ITRC FR 97-4

Prepared by

Richard K. Romick-Allen, Susan M. Morgan,
Chiang Lin, and Rex Pierce
School of Engineering
Southern Illinois University Edwardsville
Edwardsville, Illinois

December 1999

Illinois Transportation Research Center
Illinois Department of Transportation

ILLINOIS TRANSPORTATION RESEARCH CENTER

This research project was sponsored by the State of Illinois, acting by and through its Department of Transportation, according to the terms of the Memorandum of Understanding established with the Illinois Transportation Research Center. The Illinois Transportation Research Center is a joint Public-Private-University cooperative transportation research unit underwritten by the Illinois Department of Transportation. The purpose of the Center is the conduct of research in all modes of transportation to provide the knowledge and technology base to improve the capacity to meet the present and future mobility needs of individuals, industry and commerce of the State of Illinois.

Research reports are published throughout the year as research projects are completed. The contents of these reports reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Transportation Research Center or the Illinois Department of Transportation. This report does not constitute a standard, specification, or regulation.

Neither the United States Government nor the State of Illinois endorses products or manufacturers. Trade or manufacturers' names appear in the reports solely because they are considered essential to the object of the reports.

Illinois Transportation Research Center Members

Bradley University
DePaul University
Eastern Illinois University
Illinois Department of Transportation
Illinois Institute of Technology
Lewis University
Northern Illinois University
Northwestern University
Southern Illinois University at Carbondale
Southern Illinois University at Edwardsville
University of Illinois at Chicago
University of Illinois at Urbana-Champaign
Western Illinois University

Reports may be obtained by writing to the administrative offices of the Illinois Transportation Research Center at 200 University Park, Edwardsville, IL 62025 [telephone (618) 650-2972], or you may contact the Engineer of Physical Research, Illinois Department of Transportation, at (217) 782-6732.

1. Report No. ITRC FR 97-4		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Acoustics of Sound Transmission Over Noise Barrier Walls				5. Report Date December 1999	
				6. Performing Organization Code	
7. Author(s) Richard K. Romick-Allen, Susan M. Morgan, Chiang Lin, Rex Pierce				8. Performing Organization Report No.	
9. Performing Organization Name and Address School of Engineering Southern Illinois University Edwardsville Edwardsville, Illinois 62026				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. IIB-H2, FY 97	
12. Sponsoring Agency Name and Address Illinois Transportation Research Center 200 University Park Drive Edwardsville, Illinois 62025				13. Type of Report and Period Covered Final Report November 1997 through May 1999	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>The objective of this study is to access and quantify the prediction means for traffic noise. Of particular interest is the noise reduction behind noise walls, referred to as the shadow zone. The study measured traffic noise at four sites in the metropolitan Chicago area with noise barriers. These four sites were modeled with both STAMINA 2.0 and FHWA TNM 1.0. For these four sites, TNM predicted the observed traffic noise more accurately than STAMINA. In general STAMINA over predicted the traffic noise relative to the measured values.</p> <p>The second objective of the study was to access the state-of-art of top treatments for noise walls. Top treatments are an addition to a traditional noise wall to increase the effectiveness without significantly increasing the cost or height of the noise wall. It appears that top treatments are not well enough developed for consideration in Illinois at this time.</p> <p>The last objective was to develop a means to help educate the general public about traffic noise and noise wall characteristics. To meet this objective, two means were developed. The first was a home page that provides great flexibility due to the hypertext format. The second was a tri-fold brochure to serve as a hand out at public meeting or as a visual aid for one-on-one discussions.</p>					
17. Key Words Traffic Noise Noise Barrier Walls TNM, STAMINA			18. Distribution Statement No Restrictions. This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 98	22. Price

EXECUTIVE SUMMARY

Acoustics of Sound Transmission Over Noise Barrier Walls

Project IIB-H2, FY97
Report No. ITRC FR 97-4

Prepared by
Richard K. Romick-Allen, Ph.D., P.E.,
Susan M. Morgan, Ph.D., P.E.,
Chiang Lin, Ph.D., and
Rex Pierce

December 1999

Between December 1997 and May 1999 the accuracy of the current Federal Highway Administration (FHWA) traffic noise prediction models were studied and an educational aid to inform the general public about traffic noise issues was developed. As part of the project, the literature on traffic noise was reviewed, with emphasis on traffic noise prediction. One specific aspect of the literature review was to assess the current state-of-the-art of noise barrier walls with top treatments. The FHWA traffic noise prediction programs STAMINA 2.0 and TNM 1.0 were evaluated and tested utilizing a series of field measurements.

Field Traffic Noise Measurements

Field traffic noise measurements were used to assess the two FHWA traffic noise prediction programs STAMINA 2.0 and TNM 1.0. Field measurements were made at four sites in the Chicago metropolitan area using the traffic noise measurement procedure FHWA-PD-96-046 [Lee et al., 1996]. Traffic noise at each site was recorded at distances of 25, 50, 100, and 200 ft behind the barrier, at a height of 5 ft, as well as at a reference location above the barrier. These four sites were modeled in STAMINA and TNM based on site construction drawings.

In general, STAMINA over-predicted the measured noise levels. The mean over-prediction was 2.2 dBA, but the differences between measurement and predictions ranged from 4.43 to -1.48 dBA. The majority of the STAMINA predictions were above a 95% confidence limit for the measured data, indicating a poor prediction of the measured data. STAMINA with the updated noise coefficients reduce the over-prediction by about 1 dBA, so that on average the over-prediction was 1.32 dBA. Despite the improvement of the updated noise coefficients, about half of the predictions were still outside the 95% confidence limit, suggesting only a moderate agreement between measurement and predictions. Even though the STAMINA predictions were not statically significant at a 95% level, the over-predictions were generally lower than indicated by other researchers. TNM showed a slight under-prediction; the mean difference was 0.33 dBA while the differences between predictions and measured noise levels ranged from 1.31 to -1.98 dBA. The TNM noise predictions were generally within the 95% confidence limits for the measured noise levels, indicating good statistical agreement between measured and predicted noise levels.

refinement before they can be considered for field application.

Analysis tools to predict the improvement for a top treatment are not readily available. The traffic noise analysis programs of STAMINA and TNM are not able to assess the noise reduction due to top treatments. Many of the researchers studying top treatments use self-written boundary element method (BEM) programs. Most of these research analysis programs are not refined for application design studies. Therefore, it is concluded that additional research and refinement should occur before top treatments be considered for use on noise barriers in Illinois.

Tools to Discuss and Educate the General Public About Traffic Noise

Tools were developed to aid noise professionals in discussing traffic noise behavior with the general public and to establish realistic expectations from noise barriers. These tools include a home page, hypertext tool and a tri-fold brochure. The primary tool was developed using a home page format to allow the users to seek out the information that is of most interest. The tool has a generous number of graphical figures with a minimum of text. Even though the educational tool was developed using a home page format, it does not have to be made available through the Internet; it can run on a stand-alone personal computer. The tri-fold brochure is a selection of the figures from the home page tool. The brochure is intended to support one-on-one discussions or be used as a handout for public meetings.

Updating Vehicle Noise Coefficients in STAMINA

The literature review indicated that one of the significant concerns with the STAMINA 2.0 program is its reported over-prediction of traffic noise [Bowlby, 1992]. So, the project team investigated updating the vehicle noise coefficients in STAMINA to correct the over-prediction. The investigators used traffic noise emission levels (REMELs) that were recently measured by Fleming et al. [1995] for TNM and fit them to the vehicle noise equations used in STAMINA. These updated noise coefficients in STAMINA were evaluated using a series of four example problems. The example problems were modeled in STAMINA 2.0 and TNM 1.0. TNM was used as a reference in evaluating if the updated noise coefficients would reduce the over-prediction. It was concluded that the average STAMINA over-prediction of approximately 3 dBA was reduced by about 1.5 dBA with the updated noise coefficients. Despite this improvement, updating the vehicle noise coefficients in STAMINA does not alter the basic algorithms and the insertion losses (IL) were essentially unchanged [Romick-Allen et al., 1999].

Illinois Transportation Research Center Project

IIIB-H2, FY97

Acoustics of Sound Transmission Over Noise Barrier Walls

Richard K. Romick-Allen, Ph.D., P.E., Associate Professor - Principal Investigator
Susan M. Morgan, Ph.D., P.E., Assistant Professor
Chiang Lin, Ph.D., Professor and Chair of Civil Engineering, and
Rex Pierce, Instructor

**Southern Illinois University Edwardsville
School of Engineering**

Report ITRC FR 97-4

Technical Review Panel

Michael T. Bruns - IDOT Division of Highways - Design and Environment - Chair
Michelle Mahoney - IDOT District 1
Mitchell Rogers - IDOT District 1
Arlene Kocher - IDOT Division of Highways
John C. Heme - Illinois State Toll Road Authority

Table of Contents

Chapter 1 Introduction	
1.1 Project Objectives	1-1
1.1.1 Part A - Literature Review	1-1
1.1.2 Part B - Noise Barrier Modeling and Prediction	1-1
1.1.3 Part C - Top Treatments	1-2
1.1.4 Part D - Recommendations	1-2
1.1.5 Part E - Final Report	1-2
Chapter 2 Part A - Literature Review	
2.1 Traffic Noise and Its Impact on Humans	2-1
2.2 Traffic Noise Prediction and noise models	2-2
2.2.1 FHWA Models - STAMINA and FHWA TNM 1.0	2-2
2.2.2 Other Geometric Acoustics Models	2-3
2.2.3 Boundary Elements and Finite Element Acoustic Models	2-3
2.3 Other Traffic Noise Issues	2-4
2.3.1 Environmental Influences on Traffic Noise	2-4
2.3.2 Shadow Zone	2-5
Chapter 3 Part B - Noise Barrier Modeling and Prediction	
3.1 FHWA Traffic Noise Prediction Models.....	3-1
3.1.1 STAMINA and OPTIMA	3-1
3.1.2 FHWA TNM 1.0	3-2
3.1.3 FHWA TNM Concerns	3-3
3.2 Fitting TNM's REMEL to STAMINA	3-4
3.2.1 TNM and STAMINA vehicle emission equations	3-4
3.2.2 Fitting 1995 REMEL to STAMINA equations	3-5
3.2.3 Example Problems	3-8
3.2.4 Discussion	3-16
3.2.5 Conclusions and Recommendations	3-16
3.3 Field Measurements	3-17
3.3.1 Traffic Noise Measurement Protocol	3-17
3.3.2 Site Selection	3-19
3.3.3 Noise Measurement Results	3-23
3.3.4 Discussion of Field Measurement and Analysis	3-31
3.3.5 Measurement Conclusions	3-33
3.4 Influence of FHWA TNM 1.0 Features	3-34
3.4.1 Ground Zones	3-34
3.4.2 Terrain Lines	3-35
3.4.3 Entrance Ramp Modeling	3-36
3.4.4 Shadow Zone - TNM and STAMINA	3-36
Chapter 4 Top Treatments	
4.1 Types of Top Treatments	4-1
4.1.1 Wide - Double Edge Barriers	4-1

4.1.2 T and Y Top Barriers	4-1
4.1.3 Round or Elliptical Top Barriers	4-2
4.1.4 Multiple Barriers	4-2
4.1.5 Random Edge Barriers	4-5
4.2 Absorptive and Soft Faces on Barriers	4-5
4.3 Active Noise Control to Improve Barrier Performance	4-7
4.4 Analysis to predict top treatment effectiveness	4-7
4.5 Summary and Conclusions	4-11
 Chapter 5 Aids for Communicating Traffic Noise Issues with General Public	
5.1 Means to Discuss Noise Barriers with the General Public	5-1
5.2.1 Homepage - hypertext traffic noise guide	5-1
5.2.2 Tri-fold brochure	5-2
 Chapter 6 Summary	
6.1 Summary and Recommendations	6-1
6.2 Potential Future Studies and Unanswered Questions	6-1
 References	R-1
 Appendix	
A - Highway Traffic Noise - Homepage format	A-1
B- Tri-fold brochure - Highway Traffic Noise	B-1

List of Figures and Tables

Figures

2-1	Wind effect on noise propagation [Daigle et al., 1998]	2-4
2-2	Hajek [1983] contour plots from STAMINA 1.0	2-5
2-3	Junger [1975] IL contour plots for parallel barrier in cut section.	2-6
2-4	Fujiwara et al. [1998] contour plot for soft, T-top barrier.	2-7
3-1	Vehicle REMEL with speed - Automobiles	3-6
3-2	Vehicle REMEL with speed - Medium Trucks	3-6
3-3	Vehicle REMEL with speed - Heavy Trucks	3-7
3-4	TNM 1.0 verification problem.	3-7
3-5	I-78 in Pennsylvania, from University of Louisville.	3-8
3-6	Route 59 in Streamwood, IL	3-9
3-7	I-355 north of Army Trail in Addison, IL.	3-10
3-8	Reference microphone above the wall	3-18
3-9	Microphone with windscreen	3-18
3-10	Video camera used to record the traffic volumes	3-18
3-11	Weather station	3-19
3-12	Farmwood Park, Addison - I290	3-20
3-13	Corrugated concrete panels at Maple Street.	3-21
3-14	Wooden barrier at video camera location.	3-21
3-15	Martin Park ariel view	3-22
3-16	Backhoe operating near Martin Park site	3-22
3-17	Hinsdale - I-294 north of 55th Street	3-23
3-18	Earthen berms at Hinsdale site.	3-23
3-19	Farmwood Park analysis configuration	3-26
3-20	Comparison of predicted and measured noise levels - Farmwood Park	3-26
3-21	Differences between predicted and measured noise - Farmwood Park	3-27
3-22	Maple Street analysis	3-28
3-23	Comparison of predicted and measured noise levels - Maple Street	3-28
3-24	Differences between predicted and measured noise - Maple Street	3-29
3-25	Martin Park analysis	3-30
3-26	Comparison of predicted and measured noise levels - Martin Park	3-30
3-27	Differences between predicted and measured noise - Martin Park	3-31
3-28	Hinsdale analysis	3-32
3-29	Comparison of predicted and measured noise levels - Hinsdale	3-32
3-30	Differences between predicted and measured noise - Hinsdale	3-33
3-31	Skew view of Farmwood Park site	3-35
3-32	Skew view of Martin Park site	3-35
3-33	I-78 in Pennsylvania with terrain lines and ground zone for river.	3-36
3-34	Shadow zone - STAMINA 2.0 with $\alpha = 0.5$ - soft ground.	3-37
3-35	Shadow zone - STAMINA 2.0 with $\alpha = 0.0$ - hard ground.	3-37
3-36	Shadow zone - TNM 1.0 - Lawn.	3-38
3-37	Shadow zone - TNM 1.0 - Pavement.	3-38

4-1	Top treatments, T-top, Y-top, and round-top	4-1
4-2	Crombie and Hothersall [1994] noise levels from multiple barriers.	4-3
4-3	Crombie et al. IL improvement by adding additional panels.	4-3
4-4	Top treatments used in Watts [1996], and Watts and Morgan [1996]	4-4
4-5	Soft T-Top barrier, Fujiwara et al 1998.	4-6
4-6	Soft round top - water-wheel, Okubo and Fujiwara [1998].	4-7
4-7	TNM parallel barrier analysis for a T-top treatment - Maple Street. Reflective - NRC = 0.0.	4-9
4-8	TNM parallel barrier analysis for a T-top treatment - Maple Street. Absorptive - NRC = 0.5.	4-9
4-9	TNM parallel barrier analysis for a T-top treatment - Farmwood Park. Reflective - NRC = 0.0.	4-10
4-10	TNM parallel barrier analysis for a T-top treatment - Farmwood Park. Absorptive - NRC = 0.5.	4-10

Tables

3-1	Updated STAMINA REMEL coefficients	3-5
3-2	Comparison of predictions - TNM 1.0 verification problem	3-11
3-3	Comparison of predictions - I-78 in Pennsylvania	3-12
3-4	Comparison of predictions - Route 59 in Streamwood, IL	3-13
3-5	Comparison of predictions - I-355 in Addison, IL	3-14
3-6	Traffic volumes	3-24
3-7	Off-set STAMINA REMEL coefficients	3-25

Chapter 1 Introduction

The federal highway system has had a significant impact on the economy of the United States and the life style of its citizens. Commerce and the economy have benefited through transportation of goods and opening up of markets. Highways have provided an alternative transport mode that has proven to be highly dynamic. Highways also allowed factories to be located further from raw materials. In addition, the federal and state highway system has allowed citizens to easily travel for both business and pleasure. Vacationing by car has become an American tradition.

The highway system also negatively impacts society. There has been a cost to the expansive highway system. Highways allowed people to easily travel to remote locations. Commerce has increased but pollution and environmental damage also have also escalated. Multi-lane highways allowed increased traffic volumes and increased travel speeds, resulting in increased traffic noise.

Traffic noise does not permanently damage the environment, but some citizens consider it an annoyance. Traffic noise cause demands for noise abatement or mitigation. The most common means of traffic noise mitigation have been noise barriers. Noise barriers are either wall-like structures or berms, or a combination of the two. Noise barriers "reduce" traffic noise but do not eliminate noise. Even after the construction of expensive noise barriers, traffic noise may still be pronounced.

1.1 Project Objectives

This project was funded by ITRC to meet the following objectives.

- To characterized and quantify the effectiveness of noise walls using the existing FHWA traffic noise prediction programs.
- To study the effectiveness of changing the shape and/or material at the top of the noise walls as a means of increasing the effectiveness without increasing height.
- To make recommendations regarding the potential cost impacts of alternative top treatments.
- And to develop recommendations for explaining the benefits and costs of noise barrier walls to the public at large.

The project activities to satisfy these goals are as follows.

1.1.1 Part A - Literature Review

Selected traffic noise literature was reviewed and is presented in Chapter 2. There have been numerous studies conducted over the last thirty years on traffic noise issues. Interest in traffic noise seems to have intensified in the last ten years. The literature on top treatments is reviewed separately in Chapter 4.

1.1.2 Part B - Noise Barrier Modeling and Prediction

The FHWA computer programs to predict traffic noise and noise barrier performance are

examined in Chapter 3. The TNM program is very new, so there is little experience in its use. As a result, some of the features were examined to gain a better understanding of their influence on the predicted noise levels. One of the objections to the noise prediction program STAMINA is its over-prediction of traffic noise. The updating the traffic noise coefficients in STAMINA was examined to correct this over-prediction. In addition, field measurements were made at four sites in the metropolitan Chicago area. Site specific data were used in STAMINA 2.0 and FHWA TNM 1.0 to predict noise levels. These predictions were compared to the actual measured noise levels, to assess the accuracy of the prediction models for traffic in Illinois.

The analyses with TNM were not included in the original project proposal. When this project was being proposed, TNM had been delayed and the FHWA was not sure when it would be released. TNM was examined as part of this study as it was released during the term of the project.

1.1.3 Part C - Top Treatments

Top treatments are intended to increase the effectiveness of noise barriers with only marginal increase in barrier height. In Chapter 4 the literature regarding the effectiveness of top treatments was examined and summarized. Then the FHWA traffic noise prediction programs were evaluated to see if they can be used to assess the effectiveness of top treatments for use in Illinois.

1.1.4 Part D - Recommendations

Study recommendations are presented in Chapter 6.

A Chapter 5 was added to include materials developed to aid in discussing traffic noise issues with the general public. Two means developed as detailed in the original proposal. One of the means is a general traffic noise educational tool in a web page format, which could be used at public hearings and/or posted on a web site for general public access. The second means is a tri-fold brochure for one-on-one discussions or as a handout at meetings.

1.1.5 Part E - Final Report

This document is the final report and concludes the study. Even though this study has concluded, additional concerns relative to traffic noise analysis were uncovered. These concerns and suggestions for future studies are included with the recommendations in Chapter 6.

Chapter 2 Part A - Literature Review

Traffic noise has been extensively studied for the at least the last 30 years. Interest and concern with traffic noise has intensified over the last 10 years. The interest in traffic noise may be due to general concern for the environment and health.

This chapter reviews selected literature on traffic noise. Three main topics in traffic noise are considered in this review. First, the basic characteristics of traffic noise is examined and its impact on humans. Second, current models to predict traffic noise are discussed. Third, other noise issues are examined that include environmental influences on noise propagation and the shadow zone behind noise barriers.

2.1 Traffic Noise and Its Impact on Humans

Normal level of traffic noise is in the range of 60 to 85 dBA, which is below the level to cause hearing damage. The Occupational Safety and Health Administration (OSHA) set the threshold for monitoring industrial noise exposure at 80 dB and the 8 hour exposure level at 90 dB [Beranek and Ver, 1992]. Even though traffic noise levels are not likely to damage hearing, the general public may still complain that traffic noise interferes with their activities or is an annoyance. Interference with normal conversation has been reported to start at noise levels around 52 to 58 dBA [FHWA, 1980]. Studies into the relationship between noise and interruption of human sleep have been inconclusive; some subjects were awakened by relatively quiet sounds and others were not disturbed by relatively loud noises (on the order of 70 dB) [FHWA, 1980]. The potential for noises to annoy people is hard to characterize, because reaction to noises is subjective. Also the reaction to some noises depends on the time of day and the perceived "normal-ness" of the noise. For example, a dog barking in the afternoon may go unnoticed, but the same dog barking at midnight might be annoying. This is similar to characterizing people's taste in music. What one person enjoys and calls music may be an annoying noise to someone else.

An extensive overview of traffic noise was reported by Bolt, Breakneck, and Newsman in NCHRP 173 [1976]. Five sources of vehicle noise were identified and examined. These sources were engines and gearboxes, exhaust systems, fans, intake, and tires. For each source, the typical spectrum and generation parameters were discussed. The most significant sources of noise are tires and exhaust systems. Missing from the list of noise sources is aerodynamic noise.

Both Bolt et al. and Fleming et al. [FHWA-PD-96-008, 1996] indicate that traffic noise is a function of speed, volume, and mix of vehicle types. Bolt et al. measured vehicle noise between 35 to 65 mph. Recently, Fleming et al. measured vehicle noise at low speeds and concluded that a constant noise level should be added to the speed dependent noise. The traffic noise models assume that vehicle noise is logarithmic with respect to speed. Bolt et al. suggested that traffic noise should be adjusted by a factor proportional to the logarithm of the traffic volume in vehicles per hour. In the FHWA traffic noise model FHWA-RD-77-108, the traffic volume adjustment is divided by the average vehicle speed before taking the

logarithm [Barry and Reagan, 1978]. The mix of vehicle types also influences the traffic noise levels. Bolt et al. considered only two vehicle types: automobiles and trucks. The FHWA 77-108 traffic noise model considers three vehicle types: automobiles, medium trucks, and heavy trucks. Fleming et al. considered five vehicle types: automobiles, medium trucks, heavy trucks, buses, and motorcycles. Fleming et al. also considered three pavement types, influence of grades, and accelerating conditions that occur on entrance ramps and at traffic control devices.

2.2 Traffic Noise Prediction and noise models

Various models have been developed for traffic noise prediction and are in current use. These models are based on varying assumptions. The selected traffic noise prediction models reviewed include those approved by FHWA, other popular prediction means based on geometric acoustics, and numerical means to solve the acoustic differential equation.

2.2.1 FHWA Models - STAMINA and FHWA TNM 1.0

The FHWA has a long history of involvement with traffic noise prediction. The first nationally recognized traffic noise prediction model FHWA-RD-77-108 [Barry and Reagan, 1978] was a procedure based on manual table calculations. The table procedure was computerized in Standard Method in Noise Analysis or STAMINA 1.0 [Rudder et al., FHWA-RD-78-138, 1979]. STAMINA 1.0 was a main-frame computer program developed while punch cards were commonly used for data input. In 1982 the original STAMINA was revised as version 2.0 to introduce the barrier design program OPTIMA [Bowlby et al., FHWA-DP-58-1, 1982]. The OPTIMA program uses the noise predictions from STAMINA and allows the user to manipulate the barrier segment heights to design a barrier. OPTIMA also has an automated mode to design an optimal barrier based on given noise reduction for a barrier or an insertion loss (IL). Insertion loss is a measure of the effectiveness of a barrier as indicated by the difference in noise levels between without barrier and with barrier).

After the development of the STAMINA, field measurements indicated acceptable agreement between STAMINA predictions and measured noise levels [Creasey and Agent, 1988]. More recently, researchers have suggested that STAMINA over-predicts traffic noise by 3 dBA and IL by 4.5 dBA [Bowlby, 1992]. Harris and Cohn [1995] have suggested that the over-prediction may be due to changes in vehicle noise emission coefficients over time. The apparent over-prediction may be reduced by measuring updated vehicle noise emission coefficients.

In addition to the over-prediction, STAMINA is not user friendly because of its input file format and general lack of graphical input or output. The input file is cryptic and difficult to construct due to its fixed-format style. Some researchers like Cohn and Harris at University of Louisville and Bowlby formerly at Vanderbilt have developed pre- and post-processors to provide graphical and CAD interfaces to STAMINA.

To counter the limitations of STAMINA, the FHWA contracted with the Volpe Transportation Research Center to develop a new traffic noise analysis program. Then

FHWA released the new traffic noise prediction model TNM 1.0 in March 1998. To improve usability and accessibility, TNM is a PC Windows-based program. This model uses geometric acoustics (ray-tracing) with features to account for complex ground and atmospheric noise attenuation. In addition, TNM features graphical input from either CAD files or digitizers.

2.2.2 Other Geometric Acoustics Models

Additional methods to predict traffic noise and barrier attenuation are in use around the world. A general method to predict traffic noise and noise barrier attenuation has been published as International Standard ISO 9613-2 Acoustics -- "Attenuation of sound during propagation outdoors -- Part 2: General method of calculation." This procedure is widely used in Europe. The algorithms are octave-based for point sources or collections of point sources. Daigle et al. [1998] indicated that many countries rely on table or graphical calculation methods that are not computerized. For example, the UK and Japan tend to rely on charts. Japan uses design charts based on Maekawa's charts published in 1988.

In addition to those previously noted, a number of other computerized traffic noise prediction models are in use around the world. These models have been extensively reviewed by Klingner et al. [CTRO-1471-1, 1996] and Daigle et al. [1998]. These computerized models use ray-tracing or geometric acoustic methods similar to STAMINA and FHWA TNM. They include:

- IMAGE-3 [Bowlby and Cohn, 1987],
- BARRIER 2.1 - FHWA. 1990 - handles parallel barriers and was developed for Dulles project,
- Tilted Parallel Barrier Program (TPBP) [Lee et al. 1988, and Slutsky and Bertoni, 1988],
- TrafficNoiseCAD - Bowlby and Associates - graphical interface using standard CAD programs for STAMINA,
- SoundPLAN - German program handles highways, railroads, and air traffic noise,
- SOUND32 - used by CAL-DOT.
- Community Noise Model - developed by University of Southern Florida, funded by the Automobile Manufacturers Association - true simulation with random moving point sources.

It appears that the Tilted Parallel Barrier Program (TPBP) formed a significant basis for TNM, even though the TNM documentation does not indicate its origin as such. The TPBP included the environmental effects of humidity, diffractions from multiple barriers, absorptive and tilted barriers, and sound propagation over mixed terrain [Slutsky and Bertoni, 1988]. TNM also included these effects. In addition, both programs use de Jung's model [1983] for propagation of noise over mixed terrain.

2.2.3 Boundary Elements and Finite Element Acoustic Models

In contrast to the ray-tracing noise prediction programs, the numerical methods of Finite elements (FEM) and Boundary Elements (BEM) solve the wave equation (differential equation). Researchers have reported both 2-D and 3-D versions. In both the FEM and BEM analyses, the frequency or octave bands are solved individually, where an octave analysis is a

series of monotone analyses at different frequencies. A complete spectrum analysis can be very time-consuming relative to ray tracing methods. It can take from a few hours to days for a typical FEM or BEM analysis [Muradali and Fyfe, 1998]. The BEM approach has the advantage of reducing the problem to the boundary of the region to be analyzed -- uses an integral transformation. Assuming that outdoor noise propagation is essentially a semi-infinite space, then only the ground, barrier(s), and any ground features would need to be described as elements. On the other hand, the FEM analysis requires the whole region above the ground to be discretized into elements. The element size need to be small compared to the wavelength being analyzed (no bigger than $\lambda/2$, where λ is the wavelength). Due to its complexity and long run times, FEM and BEM programs are only used for research and not for day-to-day, routine traffic noise analyses.

2.3 Other Traffic Noise Issues

Additional factors are known to influence noise analysis and prediction. The influences of environmental conditions and attempts to characterize the shadow zone are discussed in the following sections.

2.3.1 Environmental Influences on Traffic Noise

The environmental or meteorological conditions of wind, humidity, and temperature influence the propagation of noise in an outdoor environment [Daigle et al., 1998, and Berengier and Anfosso-Ledee, 1998]. The atmosphere is an unsteady medium with random variations in wind, temperature, and barometric pressure. All of these variations together lead to turbulence and variability in noise transmission characteristics. The turbulence conditions become significant at larger distances from the source to influence noise propagation by some randomness.

Wind causes a refraction effect at large distances from the source (Figure 2-1). Noise propagating upwind tends to refract or bend upward, creating a reduction in noise near the ground. In the downwind direction, noise will tend to refract downward, leading to a lower

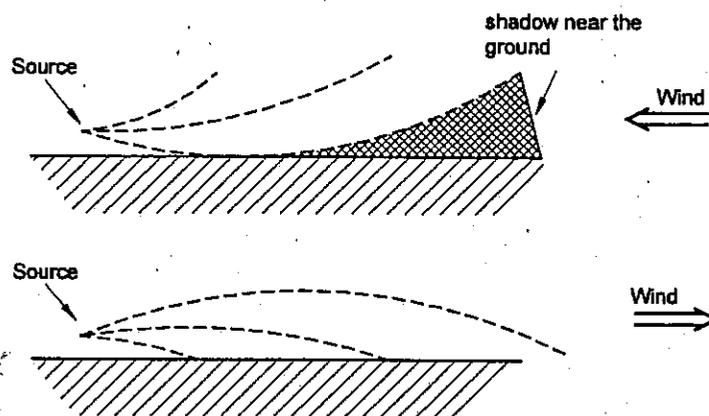


Figure 2-1 Wind effect on noise propagation [Daigle et al., 1998].

rate of attenuation. This effect is supported by full-scale barrier testing reported by Watts and Morgan [1996], who regressed observed noise against wind velocity for a constant level noise source (loud-speaker). They reported noise from 57 dBA to 63 dBA for wind velocities from -4 m/s to +2 m/s perpendicular to the barrier, or a net sensitivity of approximately 1 dBA per m/s.

Temperature gradients and temperature changes also impact noise propagation. Temperature gradients caused by ground cooling in the late afternoon create temperature inversions that have a tendency to reflect noise downward. On the other hand, morning heating of the air near the ground tends to cause sound to be refracted upwards.

Humidity directly influences the noise propagation rate as documented in ANSI standard [S1.26-1978]. Humidity effects are only pronounced at larger distances from the source. For example, Lee et al. [1988] reported that at a distance of 1000 ft (about 300 m) behind the barrier, the net acoustic attenuation of soft ground and atmosphere is approximately 9 dB per distance doubling. At distances closer to the barrier (on the order of 100 ft), the acoustic attenuation is about 4.5 dB per distance doubling, which is the value corresponding to STAMINA's alpha factor of 0.5.

2.3.2 Shadow Zone

Some researchers have shown elevation contour plots of noise levels or insertion loss behind the barrier. These plots give a glimpse into the spatial noise propagation characteristics behind a barrier. For example, Hajek [1983] produced a series of contour plots using STAMINA 1.0 in the process of studying parallel barrier effects. Single barriers on one side of the road were used as a reference (Figure 2-2). Hajek's soft ground contours show discontinuities of up to 8 dB in the contours, which is attributed to switching propagation rates when barrier diffraction is involved. Another researcher, Junger [1975] presented insertion loss contours for a depressed highway (cut section) with parallel barriers. Junger's contours for reflective and absorbing barriers were determined through scale model testing at 1,000 Hz (Figure 2-3). Recently, Fujiwara et al. [1998] studied various modifications to

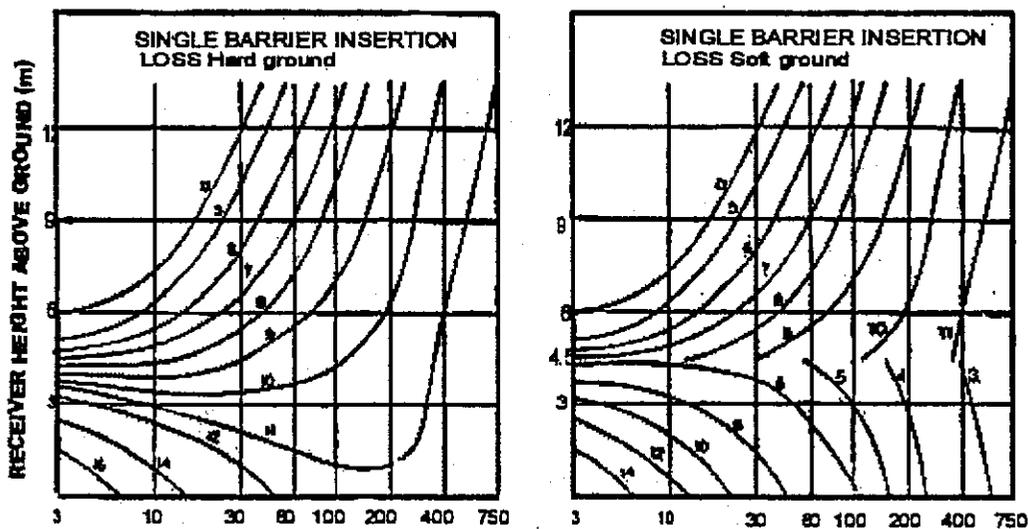


Figure 2-2 Hajek [1983] contour plots from STAMINA 1.0.

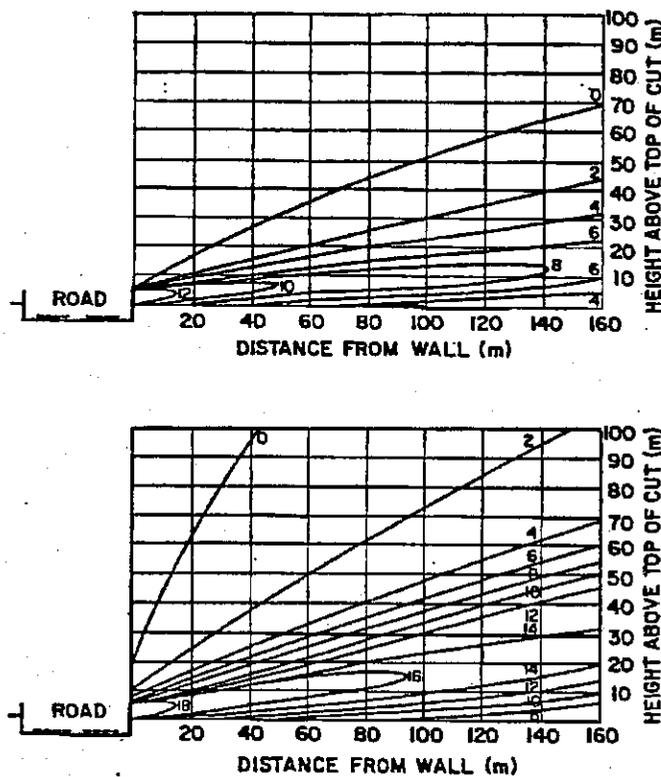


Figure 2-3 Junger [1975] Insertion loss contour plots for parallel barriers in cut section. Top - no absorptive treatment and bottom with absorptive treatment.

barriers for increasing effectiveness. Fujiwara considered a range of top treatments that included wide barriers, T-tops, and Spherical Tops all with and without noise absorbing surface treatments (see discussion in Chapter 4 for additional details). One of the special cases Fujiwara examined was a T-top treatment with an acoustically "soft" top surface (series of channels for destructive interference). Fujiwara's insertion loss contours for the soft T-top barrier are shown in Figure 2-4 for both scale model testing and from BEM analysis. Both sets of contours show a similar pattern with reasonable agreement. However, the BEM analysis predicted higher insertion loss very near the barrier and near the ground.

Even though these cited insertion loss contours came from different sources and they are for very different barrier configurations, it is interesting to note the similarities and differences. All the contours show that the insertion loss decreases at increasingly steeper rays from the top of the barrier. An 8 dB insertion loss line appears between 30° and 60° from the top edge of the barrier and slightly above the barrier. Below this 8 dB contour, the insertion loss contours flatten out and become almost parallel to the ground. This trend holds for the top half of the barriers. Then there is less similarity for the lower half and near the barrier. Fujiwara's and Hajek's contours both show the highest insertion loss near the barrier and near the ground. Near the barrier the contours are approximately perpendicular to the barrier and near the ground they are approximately perpendicular to the ground for short to moderate distances from the barrier. Junger's contours show a slightly different trend; the highest insertion losses are elliptical contours that are near the middle of the barrier and do not extend to the ground. The insertion loss decreases again near the ground.

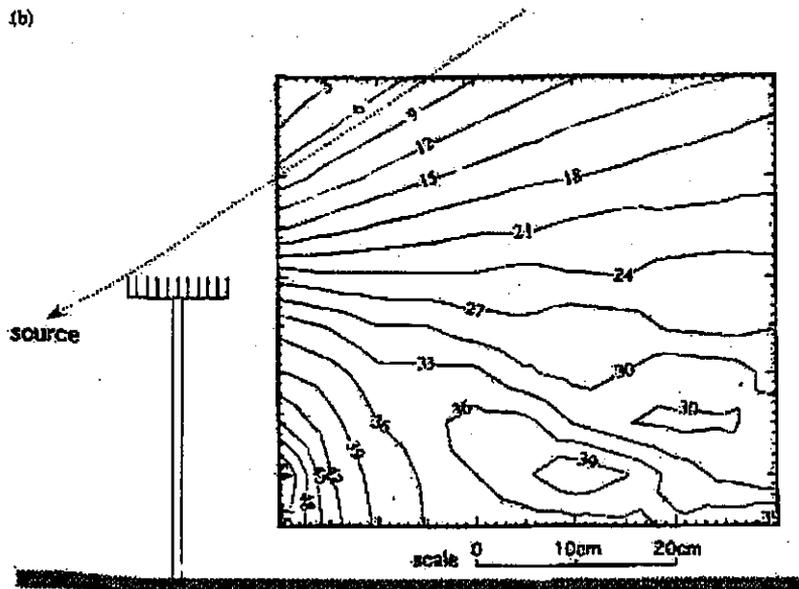
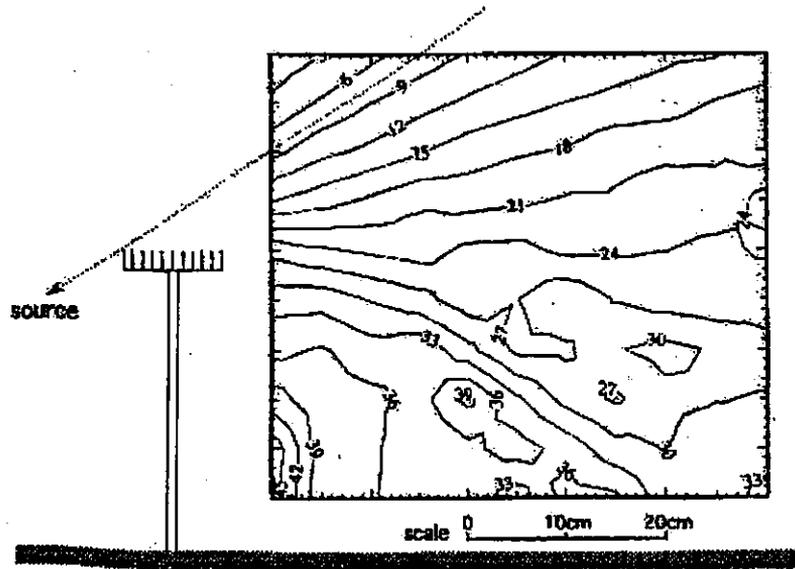


Figure 2-4 Fujiwara et al. [1998] contour plot for soft, T-top barrier. Top - scale model test contours, Bottom - BEM predicted contours.

Chapter 3 Noise Barrier Modeling and Prediction

This chapter reports the activities to characterize and quantify the effectiveness of noise barrier walls. This is done by starting with a critical evaluation of the two FHWA traffic noise prediction programs STAMINA 2.0 and TNM 1.0. Then the effectiveness of the prediction programs is assessed through a series of field measurements to compare with predictions. In addition, a method was developed to update the vehicle emission coefficients in STAMINA to correct its reported over-prediction.

3.1 FHWA Traffic Noise Prediction Models

To qualify for federal support funds, the FHWA requires an environmental noise study that includes noise predictions as part of a highway project proposal. Noise studies are required for both new highway projects (Type I) and highway expansion projects (Type II). As a result, the FHWA and the state DOTs have been actively involved in sponsoring traffic noise research and the development of traffic noise prediction models. The FHWA has funded the development of STAMINA [Rudder et al., 1979] and FHWA TNM [Menge et al., 1998]. STAMINA has been in use for about 20 years and is expected to be replaced by TNM by March 2000.

3.1.1 STAMINA and OPTIMA

The STAMINA program is essentially a computerized version of the FHWA Highway Traffic Noise Model, FHWA-RD-77-108. The 77-108 model is a manual method requiring a series of hand calculations. STAMINA was written in FORTRAN using fixed-format input and was implemented on mainframe computers that were common at the time.

STAMINA was appropriate for predicting traffic noise and barrier insertion loss (IL - reduction in noise level due to barrier), but it was not ideal for designing barriers for specific sites. The OPTIMA program was developed to assist traffic engineers with barrier design [Bowlby et al., 1982]. The OPTIMA program does not itself perform noise analyses but uses STAMINA noise predictions. To accommodate this scheme, the STAMINA program was modified to perform analyses for a range of barrier heights or perturbations. OPTIMA is an interactive program that reads the STAMINA output files and allows the operator to increase or decrease the heights of individual barrier segment heights and observe noise levels at the receivers. OPTIMA was released along with the modified STAMINA 2.0, which had minor modifications and relaxed the fixed-format input requirement. However, the input was still rigorous and not graphical.

For the past 17 years, STAMINA 2.0 has been the primary FHWA traffic noise prediction program. During that time, a few researchers have developed graphical and digitizing input means to help STAMINA be more user-friendly and to reduce errors.

The STAMINA program and the FHWA-RD-77-108 FHWA traffic noise model predict traffic noise using the Reference Energy Mean Emission Levels (REMEL - L_0) combined with a series of adjustment factors as indicated in Equation 1.

$$L_{eq}(h)_i = (\bar{L}_0)_{Ei} + 10\text{Log}\left(\frac{N_i \pi D_0}{S_i T}\right) + 10\text{Log}\left(\frac{D_0}{D}\right)^{1+\alpha} + 10\text{Log}\left(\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi}\right) + \Delta_s \quad (1)$$

The first term is the vehicle noise level, while the remaining terms are adjustments for traffic volume and speed, observer distance, finite road segment length, and shielding adjustments. The vehicle noise levels, or REMELs, are for the three vehicle types: automobiles, medium trucks, and heavy trucks. The alpha factor, α , in the distance adjustment term reflects the rate that noise decreases for a doubling of distance (DD). When $\alpha = 0$ the noise level decreases at a rate of 3 dB/DD and represents hard ground, such as pavement or water. When $\alpha = 0.5$ the noise level decreases at a rate of 4.5 dB/DD and is used to represent soft ground, such as grassland or planted fields.

The shielding adjustment (Δ_s) is used to represent noise interactions with rows of houses, dense trees, or barriers. Only barriers have an explicit equation for the prediction of shielding adjustment. The barrier shielding is based on Fresnel diffraction (Equation 2) and is predicted in 77-108 using tables based on the Fresnel number and the angles from the observer to the right and left ends of the barrier.

$$\Delta_{\text{barrier}} = 10\text{Log}\left[\frac{1}{\phi_R - \phi_L} \int_{\phi_L}^{\phi_R} 10^{\frac{-\Delta_i}{10}} d\phi\right] \quad \text{where } -\Delta_i = \Delta(N_0) \text{ and } N_0 = 2\left(\frac{\delta_0}{\lambda}\right) \quad (2)$$

STAMINA 2.0 is a monotone noise analysis, where diffraction is based only on the frequency of 500 Hz. However, the vehicle REMEL values include contributions for all frequencies. Noise levels at receivers are indicated in terms of L_{10} and L_{eq} (integrated level) in dBA.

3.1.2 FHWA TNM 1.0

According to the FHWA TNM 1.0 Technical Manual [Menge et al., 1998] the TNM computer program replaces STAMINA 2.0/OPTIMA and the TNM Technical Manual replaces the FHWA-RD-77-108 Highway Traffic Noise Prediction Model [Barry et al., 1978]. This new program has graphical and digitizing inputs, and runs on Intel PCs with the MS Windows operating systems (3.1, Win95/98, or WinNT). TNM includes many updated acoustic effects and incorporates algorithms from relatively recent acoustic research. These effects include an updated diffraction and ground propagation model from de Jong et al. [1983], house row shielding, shielding for tree zones, mixed ground propagation effects, and environmental effects of temperature and humidity. In addition, TNM uses one-third-octave bands for all calculations, although the noise levels at receivers are only provided as L_{eq} (integrated noise level) in dBA.

The basic TNM equation is shown in Equation 3:

$$L_{Aeq} = EL_i + A_{\text{Traff}(i)} + A_d + A_s = EL_i + \left[10 * \text{Log}\left(\frac{V_i}{S_i}\right) - 13.2\text{dB}\right] + 10 * \text{Log}\left(\frac{15 * \alpha}{d * 180}\right) + A_s \quad (3)$$

Similar to STAMINA, the first term represents the vehicle noise levels and the remaining terms provide adjustments for traffic volume and speed, distance, and shielding effects.

The vehicle noise emission levels, EL_i , use the vehicle REMELs from the extensive traffic noise measurement study reported by Fleming et al. [FHWA-PD-96-008, 1995]. This experimental REMEL study measured A-weighted and 1/3 octave noise emissions from approximately 6,000 vehicles in 9 states. The study considered five vehicle types: automobiles, medium trucks, heavy trucks, busses, and motorcycles. Also considered were three types of road surfaces: dense-graded asphaltic concrete (DGAC), Portland cement concrete (PCC), or open-graded asphaltic concrete (OGAC). Other factors characterized were grades, on ramps and traffic control devices, where full-throttle levels were assumed for accelerating vehicles.

In addition to the TNM REMELs, the vehicle noise levels are affected by a combination of vehicle speed and source height. Each vehicle type has two source heights, one at the road surface to indicate tire noise and the other at the vehicle exhaust height. At lower speeds (below 30 mph) the noise is primarily from the exhaust source height. At higher speeds, the tire and exhaust sources are combined to lower the source height due to increased tire noise.

The diffraction model and ground propagation is based on de Jong's model and uses the approach of Boulanger et al. [1997] to deal with mixed-impedance ground zones. The de Jong model assumes that the ground terrain influences noise propagation. So, the representation of the ground is important and is indicated through terrain lines. Over hard surfaces, such as pavement or water, the noise is abated at approximately 3 dB/DD. However, soft ground, like grassland, has a varying absorption rate. It starts at 4.5 dB/DD to around 60 m and then increases to about 9 dB at 300 m due to ground source reflections.

In addition to ground absorption, TNM incorporates variable atmospheric absorption based on the 1993 ISO standard ISO 9613-1. The atmospheric absorption is a function of temperature and humidity. However, standard FHWA traffic noise analyses should be performed at standard conditions as indicated in the FHWA analysis guidelines.

3.1.3 FHWA TNM Concerns

The FHWA TNM 1.0 program was released in March 1998. It was distributed to all State DOTs and was offered for general sale through MacTrans at Florida State University. The SIUE research team has been using TNM since its general release. During this time, a few computer bugs and questionable behavior were noted. Some of these are simply oversights by the software developers and have little impact on the results. The bugs relate to receiver adjustment factors, run-time errors, contour plots, set-up menu, and repeated tabular information.

- Receiver Adjustment Factors - The adjustment factors are, in theory, similar to STAMINA's shielding factors; however their algebraic signs are opposite. In TNM, a positive factor increases the sound level from a roadway segment to a receiver. These factors may only be input as positive values in TNM 1.0. When importing a STAMINA data file, there is a check box to import the shielding factors as adjustment factors.

Checking this box does set up the adjustment factor table, but no values appear in the tables.

- Run-time errors - We have encountered a variety of run-time errors that range from Illegal Operation (divide by zero or related math errors) to Access Violation (trying to access protected memory), all of which cause the program to terminate. In discussions with Ms. C. Lee at the Volpe Transportation Research Center, these errors seem to be related to sensitivity between elements. A small change in observer or road segment location may allow the program to complete the analysis. The study team found that about half of the analyses run for this study needed some adjustment. The fact that these significant run-time errors occurred at all is a concern. The adjusting process to allow an analysis to complete can be very time consuming; some analyses run for multiple hours before the error occurs and a trial and error process is required to make the appropriate change(s). Therefore, multiple days may be required to complete one analysis.
- Contour Plots - The IL contour plots are calculated as indicated in the user manual, but the file name prevents them from being re-read after being saved. In addition, sometimes the contours are labeled and other times they are not and the number of contours varies from analysis to analysis. The differences seem to be random and the reasons for this error are not understood. In general, producing a contour plot requires a significantly longer time than a normal TNM analysis.
- Set-up menu - Changes to items under the set-up menu are not detected as invalidating the existing calculated results. On the other hand, any change to the data accessed under the Input menu causes a warning box indicating that this change will invalidate the current results. Corresponding changes to default ground type, temperature, or humidity should also invalidate the current results. However, this warning never occurs. This is not a serious error, but requires the analyst to recognize that the results are invalid.
- Repeated information in tables - The sound level result table included repeated information in several columns. In general, the TNM tables should be reviewed to improve utility and usefulness.

3.2 Fitting TNM's REMEL to STAMINA

One of the criticisms of STAMINA is that it over-predicts traffic noise levels. Cohn and Harris [1995] have suggested that this over-prediction may be due to changes in vehicle noise emission levels. This concept was tested by fitting the recently measured vehicle noise levels for TNM to the STAMINA equations [Romick-Allen et al., 1999].

3.2.1 TNM and STAMINA vehicle emission equations

The 1995 REMEL study collected vehicle noise data from 40 sites in seven states for a wide range of conditions. These included five vehicle types, a range of speeds, three road pavement types, level roads and grade, as well as interrupted traffic flow conditions. This wide range of data was fit with a nonlinear REMEL equation for overall noise levels:

$$L_E(S) = 10 * \log \left[10^{\frac{C+\Delta E}{10}} + S^{10} \left(10^{\frac{B+\Delta E}{10}} \right) \right] \quad (4)$$

where S is the vehicle speed. The term containing C is a constant noise level term to account for engine and exhaust noise that is independent of speed. A corresponding equation is used for 1/3-octave band noise by combining Equation 4 with a sixth-order polynomial equation in frequency (f).

$$L_E(S, f) = 10 * \log \left[10^{\frac{C+\Delta E}{10}} + S^{10} \left(10^{\frac{B+\Delta E}{10}} \right) \right] - (K_1 + K_2 S) + (D_1 + D_2 S) + (E_1 + E_2 S) \log(f) + (F_1 + F_2 S) (\log(f))^2 + (G_1 + G_2 S) (\log(f))^3 + (H_1 + H_2 S) (\log(f))^4 + (I_1 + I_2 S) (\log(f))^5 + (J_1 + J_2 S) (\log(f))^6 \quad (5)$$

The STAMINA vehicle noise emission is Equation 6

$$L_{0_E}(S) = C_0 + C_1 \log(S) + 0.115 \sigma^2 \quad (6)$$

This equation is logarithmic in speed with a correction for the standard deviation of the data ($0.115 \sigma^2$). The C_1 term is similar to A, and $(C_0 + 0.115 \sigma^2)$ is similar to $(B + \Delta E)$.

1995 TNM REMEL fit to STAMINA

	C0	C1	σ	Corr. Coef.
Automobiles	1.63	41.03	2.62	0.999
Medium Trucks	28.99	28.77	2.90	0.995
Heavy Trucks	35.94	27.31	2.45	0.987

Table 3-1 Updated STAMINA REMEL coefficients.

3.2.2 Fitting 1995 REMEL to STAMINA vehicle emission equations

The STAMINA vehicle emission equation is fit to the 1995 REMEL equation using a regression method. The fitting was done using the baseline REMEL Equation 4 assuming average pavement, level grade, and no acceleration for the three vehicle types: automobiles, medium trucks, and heavy trucks. The REMEL equation was used to compute the noise levels for each vehicle type at 2 km/h speed increments. Then the STAMINA Equation 6 was fit to these levels for speeds from 40 to 120 km/h (25 to 75 mph). The standard deviations were obtained directly from Fleming et al. [1995]. The resulting new coefficients are listed in Table 3-1. The fit was excellent with regression correlation coefficients between 0.987 and 0.9999. Figures 3-1 through 3-3 show the vehicle noise levels for automobiles, medium trucks, and heavy trucks, respectively. Each figure compares vehicle noise levels for the TNM REMEL, STAMINA 1975, and the new fit values as a function of speed. In the range from 40 to 120 km/h, the TNM and new fit curves are almost indistinguishable. Although the vehicle emissions were fit for speeds as slow as 40 km/h (25 mph), the STAMINA equations and coefficients are not intended for use below 48 km/h (30 mph).

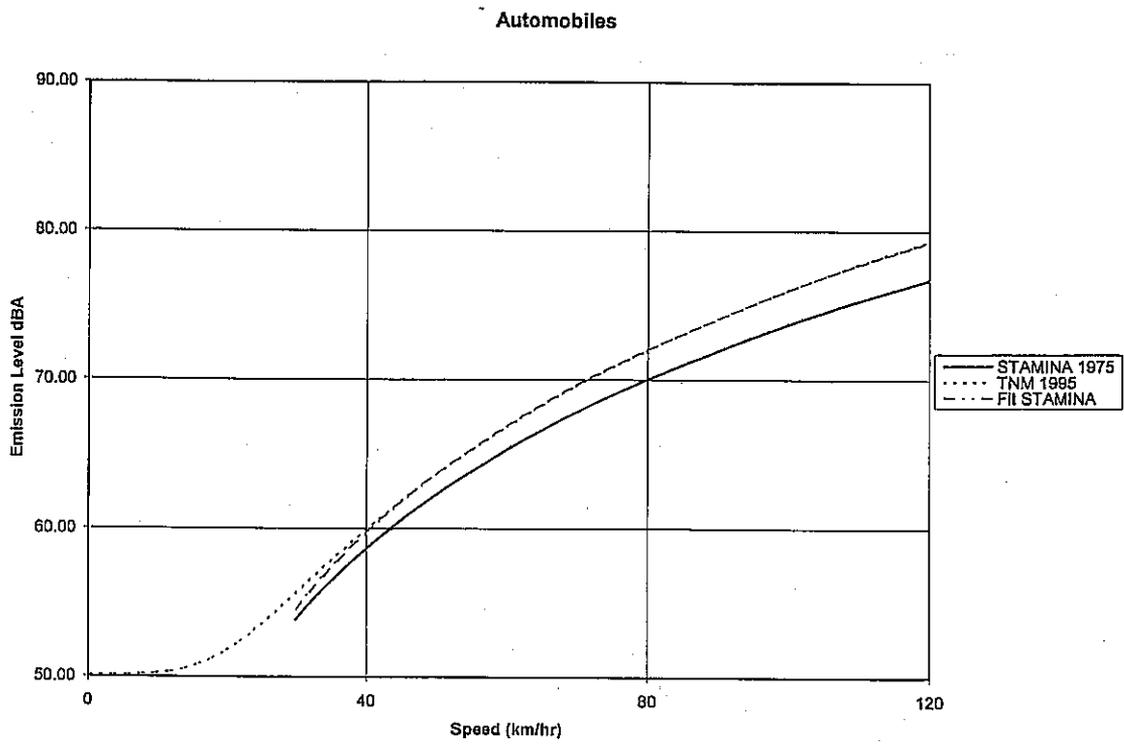


Figure 3-1 Vehicle REMEL with speed - Automobiles.

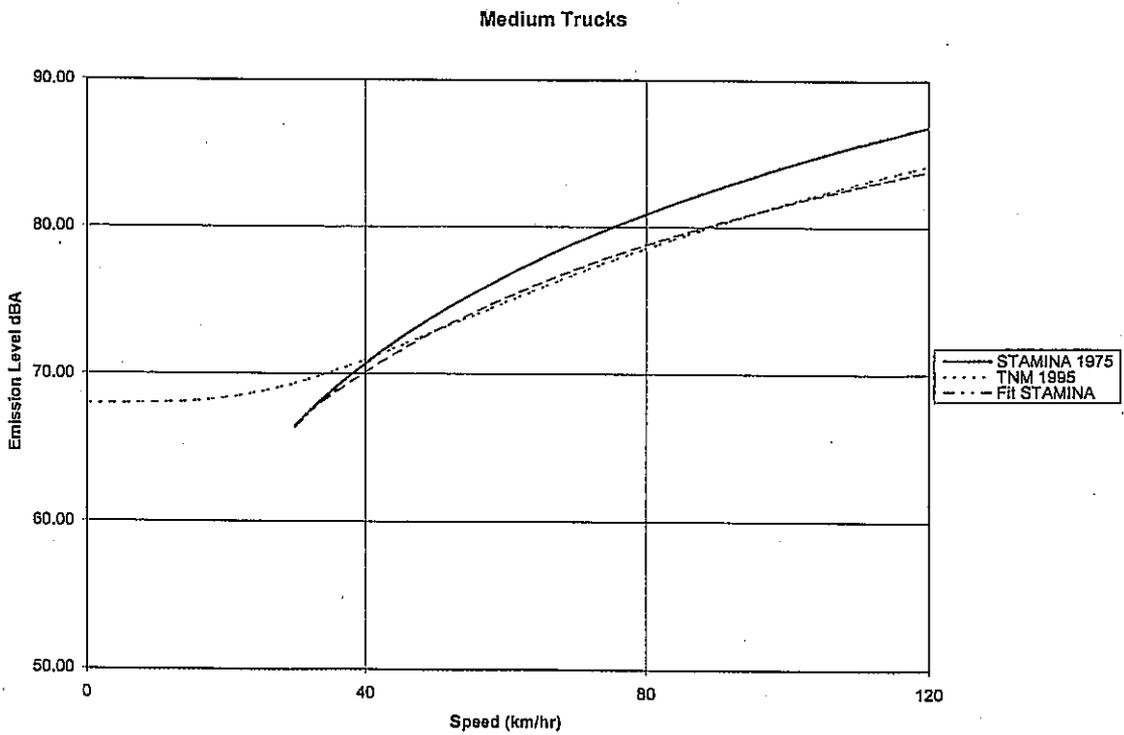


Figure 3-2 Vehicle REMEL with speed - Medium Trucks.

Heavy Trucks

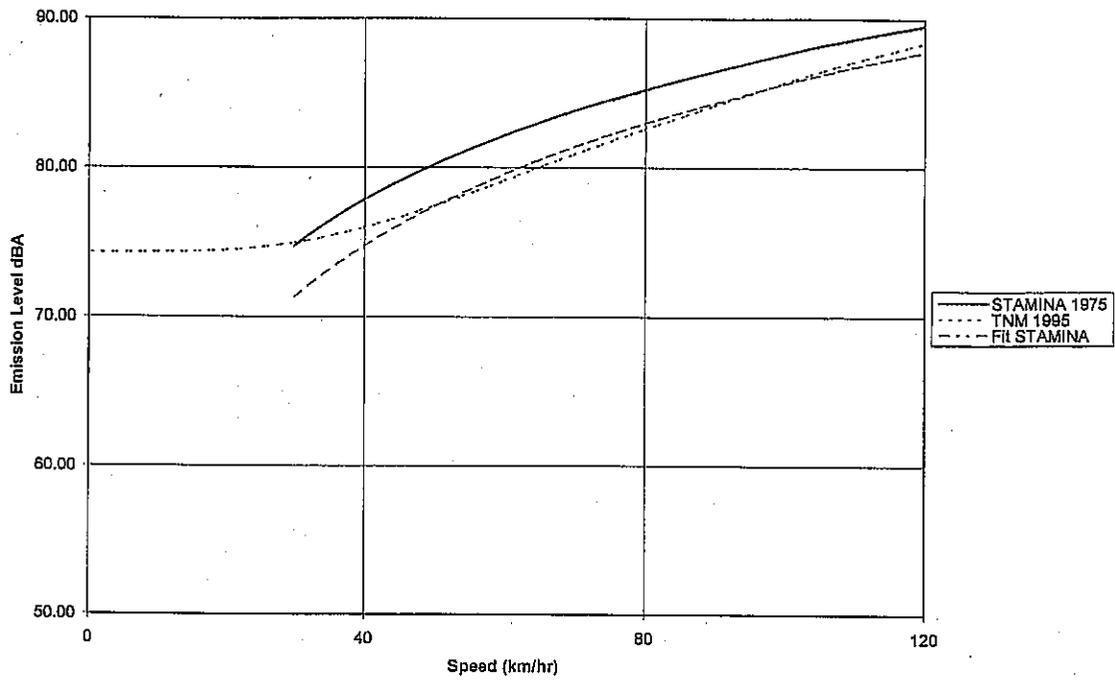


Figure 3-3 Vehicle REMEL with speed - Heavy Trucks.

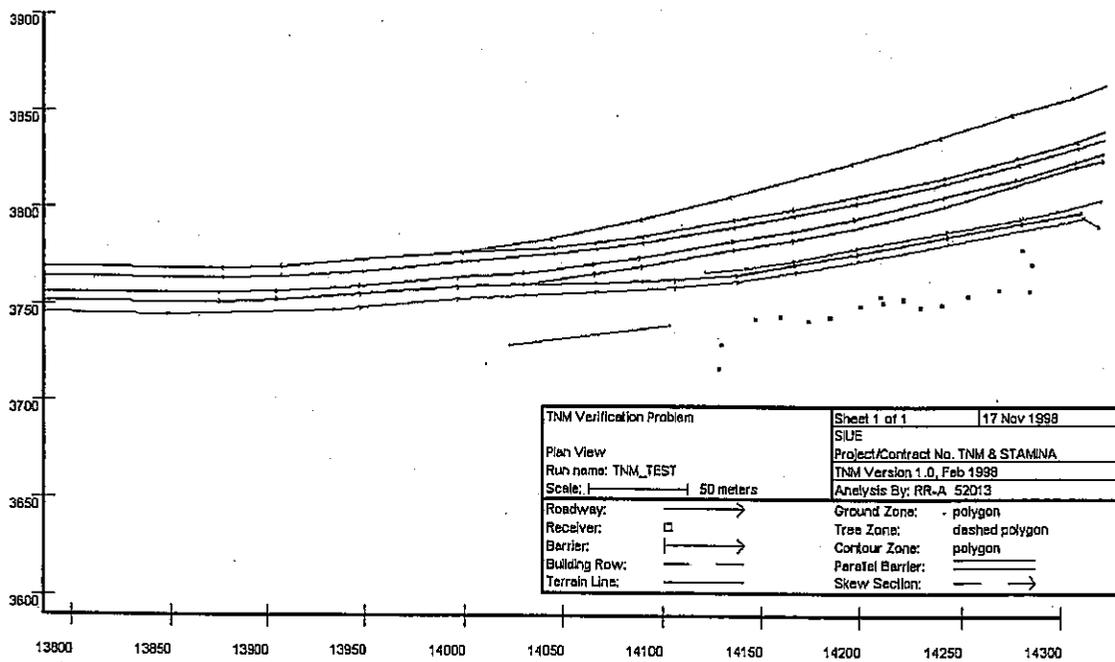


Figure 3-4 TNM 1.0 verification problem.

3.2.3 Example Problems

Four traffic noise example problems are used to evaluate the new vehicle emission coefficients in STAMINA relative to TNM 1.0 and the original STAMINA.

- TNM 1.0 verification problem, Figure 3-4. This analysis includes four main roadways - two roadways in each northbound and southbound directions, two ramps, three barriers (heights of 3.66 m (12 ft) or zero), and 32 receivers (heights of 1.52 m (5 ft) and 4.57 m (15 ft) - labeled by letters from left to right). This analysis has two barriers between the main roadways and the receivers, but only one barrier has a non-zero height. Traffic volume is approximately 5,000 vph in each travel direction of the main roadway. The traffic speed is 96.6 km/h (60 mph) on the main roadway and 72.4 km/h (45 mph) on the ramps. The main roadway's traffic includes approximately 1.1% medium trucks and 0.3% heavy trucks. The supplied file had STAMINA α factors of zero that were changed to 0.5 to agree with the default TNM ground type of "Lawn". Also, the original STAMINA file had some non-zero shielding factors, which are not treated the same between STAMINA and TNM. To avoid confusion, the shielding factors were set to zero.

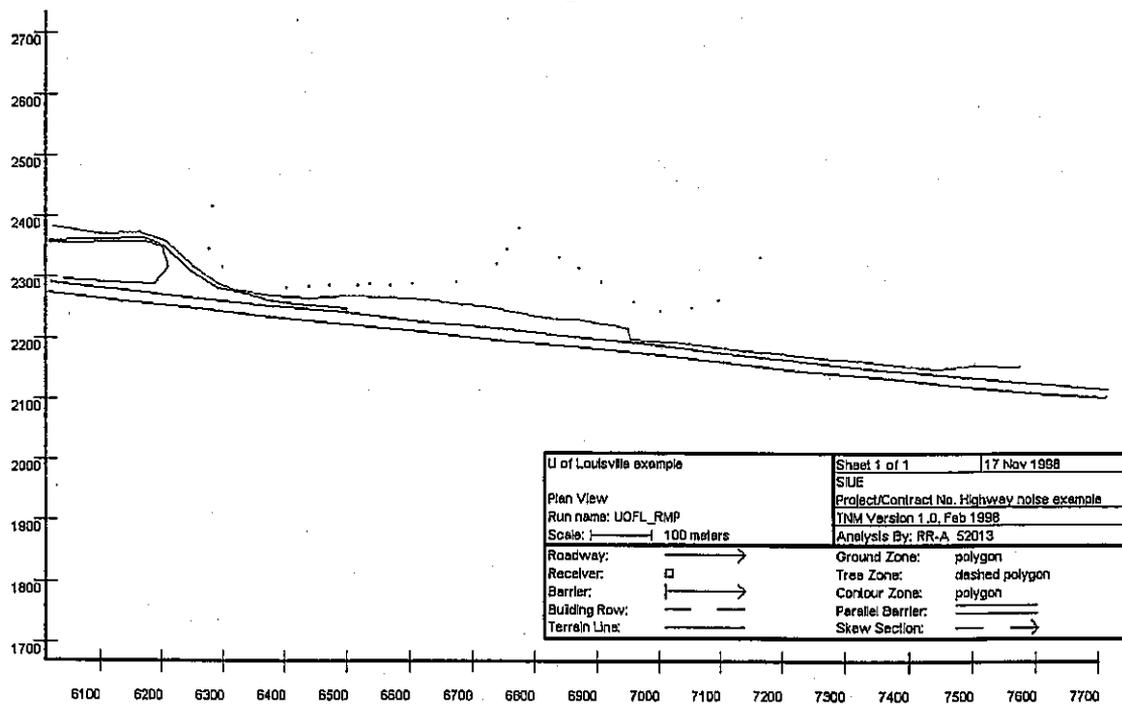


Figure 3-5 I-78 in Pennsylvania, from University of Louisville.

- I-78 in Pennsylvania, Figure 3-5. The STAMINA data file was obtained from the University of Louisville. This analysis includes four roadways: two main highway travel directions (on-grade on left side and cut-section on right side) and two ramps; a single continuous barrier, and 27 receivers (numbered left to right, with the majority on a ridge above the highway). The main travel speed is 88.5 km/h (55 mph). The eastbound traffic volume is 2100 vph and westbound traffic volume is 3100 and 2500 vph, before and after ramps respectively (entrance ramp modeled in TNM). The main traffic includes about 2.5% medium trucks and 15% heavy trucks. This analysis site had fairly complex terrain. (See Section 3.4.2 for a discussion on terrain lines)

- Route 59 in Streamwood, IL, Figure 3-6. This analysis includes two roadways (on grade), two barriers with a gap for an intersecting roadway, and 14 receivers (heights of 1.52 m (5 ft) and 3.04 m (10 ft), numbered from left to right). The traffic volume is 2200 vph (5% medium trucks and 10.5% heavy trucks) in each direction, with speeds of 88.5 km/h (55 mph) and 96.6 km/h (60 mph).

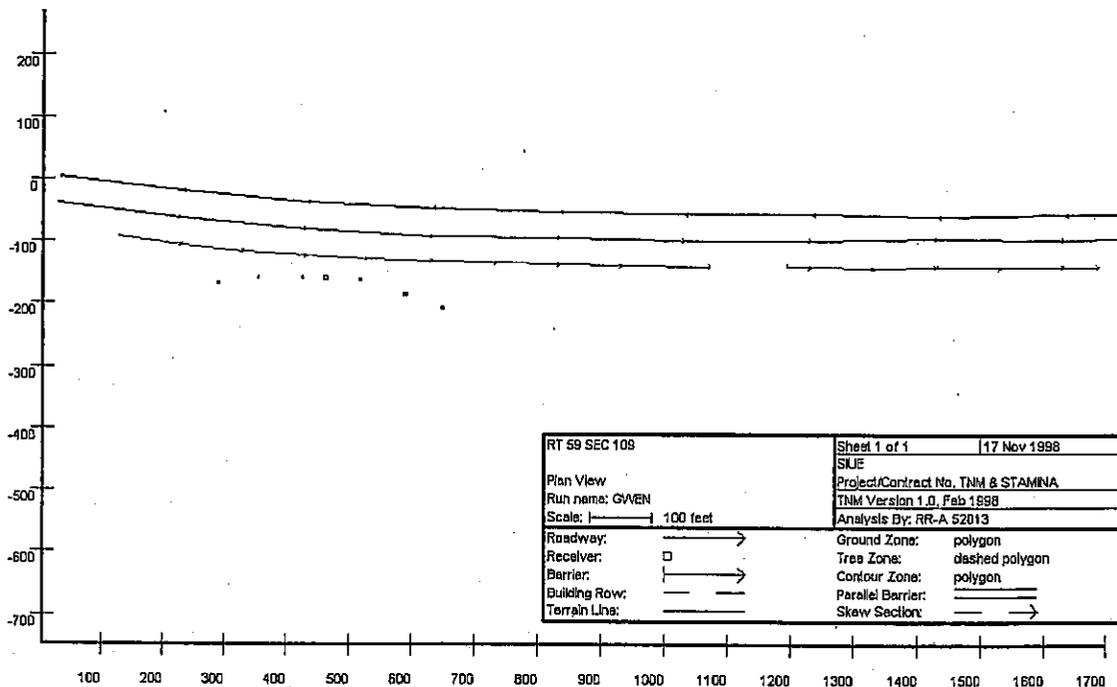


Figure 3-6 Route 59 in Streamwood, IL.

- I-355 North of Army Trail in Addison, IL, Figure 3-7. This case includes five roadways: main highway (on grade) with intersecting road and overpass, entrance ramp, one barrier, and 11 receivers (height 1.52 m (5 ft) and numbered from left to right). The main north-south highway has a total traffic volume of 2200 to 2350 vph (4.5% medium trucks and 11% heavy trucks) in each direction with vehicle speed of 88.5 km/h (55 mph). The intersecting east-west road has traffic volume of 600 vph (10% medium trucks and 8% heavy trucks) in each direction, with a speed of 80.5 km/h (50 mph). The entrance ramp has a traffic volume of 100 vph with a speed of 64.4 km/h (40 mph).

Each example was analyzed with FHWA TNM 1.0 (TNM), STAMINA 2.0 using the original 1975 FHWA emissions (S75), and STAMINA with the new emissions fit from the 1995 REMEL (S95). The TNM analyses used the default ground type of "lawn" and the STAMINA analyses had α factors of 0.5. The overall hourly equivalent noise levels (Leq) at each receiver are listed in Tables 3-2 through 3-5; the tabulated data are sorted based on distance behind the barrier. These tables also show the differences between the TNM and the two STAMINA analyses (TNM vs. S75 and TNM vs. S95). Three types of differences are listed: Insertion Loss (IL), Leq without barrier (w/o B), and Leq with barrier (w/ B).

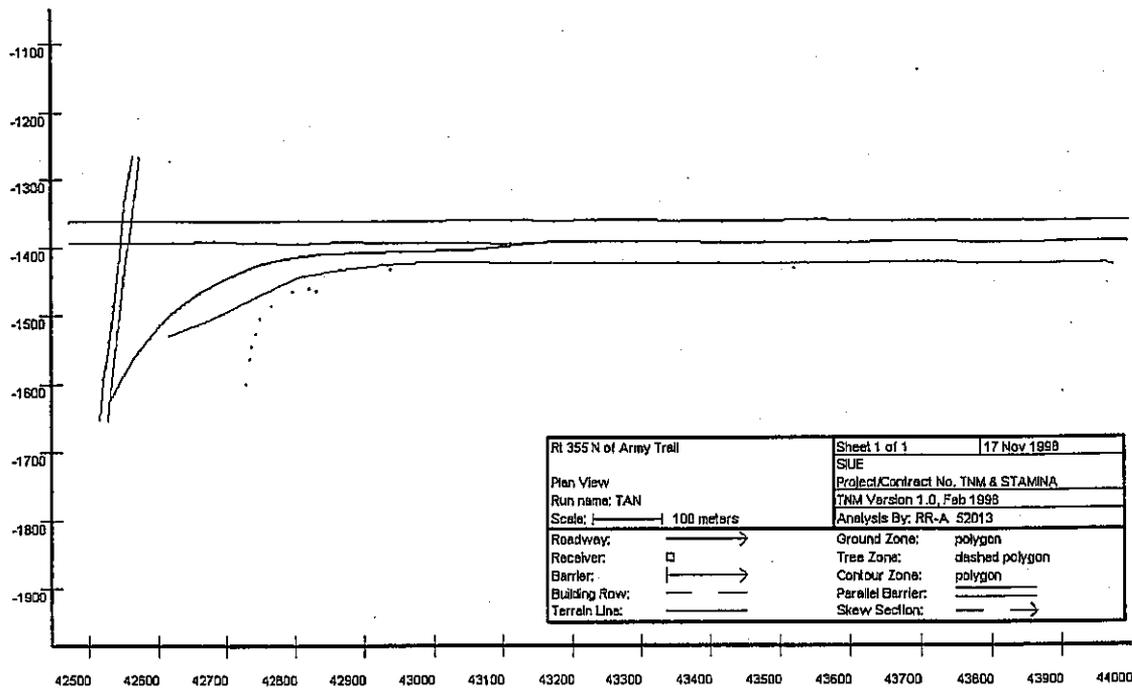


Figure 3-7 I-355 north of Army Trail in Addison, IL.

In all four test examples, the distribution of the differences is moderate as indicated by the standard deviations being less than 1.0 dBA for all but one example (I-78). The standard deviations for the TNM verification problem, RT-59, and I-355 ranged from 0.4 to 0.85 dBA. This suggests that the majority of the differences vary less than +/- 1.0 dBA from the mean difference for each set of observers. Thus, the mean differences were used in comparing the results. In addition, statistical testing was used to test for a correlation between the noise level differences and the receiver distance behind the barrier and found no statistically significance except for the I-355 example ($\alpha > 0.05$). However, a moderate to strong correlation was found for each analysis' predicted noise level and the distance of the observer behind the barrier.

TNM Verification Problem

The results of analyzing the TNM verification problem (Table 3-2) show consistent differences between TNM and the two STAMINA analyses; all the standard deviations range from 0.7 to 0.4 dBA. Only a few individual differences were outside a range of +/- 1 standard deviation. One observer, D1 (fourth from left side), consistently gave the smallest difference between TNM and the two STAMINA analyses. The maximum difference occurred at different observers for the comparisons.

The insertion loss comparison shows that the two STAMINA models have similar mean under-predictions of 3.6 and 3.7 dBA relative to TNM. Without the barrier, STAMINA analyses under-predict the traffic noise relative to TNM, but the updated traffic noise coefficients reduce the under-prediction from 2.7 to 1.2 dBA. With the barrier, both

Obs Dist (F)	TNM 1.0 lawn		STAMINA FHWA 75		STAMINA REMEL 95		Insertion Loss		DIFF W/O B		DIFF W/B		
	W/O B	W/B	W/O B	W/B	W/O B	W/B	TNM-S75	TNM-S95	TNM-S75	TNM-S95	TNM-S75	TNM-S95	
19aE-2	33	73.8	61.1	71.2	61.7	72.4	63.2	3.2	3.5	2.6	1.4	-0.6	-2.1
O-1	61	72.2	60.5	69.2	61.3	70.6	62.7	3.8	3.8	3.0	1.6	-0.8	-2.2
C-1	66	72.3	61.4	70.4	61.6	71.9	63.0	2.1	2.0	1.9	0.4	-0.2	-1.6
19aE-1	67	74.4	61.7	70.8	62.3	72.2	63.7	4.2	4.2	3.6	2.2	-0.6	-2.0
D-1	69	71.9	61.3	70.3	61.5	71.7	62.9	1.8	1.8	1.6	0.2	-0.2	-1.6
G-1	75	73.7	61.4	70.3	62.1	71.7	63.5	4.1	4.1	3.4	2.0	-0.7	-2.1
H-1	77	73.4	61.3	70.2	62.0	71.6	63.4	3.9	3.9	3.2	1.8	-0.7	-2.1
I-1	78	73.4	61.1	69.9	61.8	71.4	63.2	4.2	4.1	3.5	2.0	-0.7	-2.1
E-1	84	72.4	60.9	69.7	61.5	71.2	62.8	3.3	3.1	2.7	1.2	-0.6	-1.9
F-1	84	72.4	60.9	69.7	61.4	71.1	62.8	3.2	3.2	2.7	1.3	-0.5	-1.9
M-1	92	70.5	59.6	68.0	60.5	69.4	61.9	3.4	3.4	2.5	1.1	-0.9	-2.3
L-1	94	71.1	59.9	68.4	60.8	69.8	62.2	3.6	3.6	2.7	1.3	-0.9	-2.3
J-1	95	71.9	60.4	69.0	61.2	70.4	62.6	3.7	3.7	2.9	1.5	-0.8	-2.2
K-1	99	71.4	60.1	68.6	60.9	70.0	62.3	3.6	3.6	2.8	1.4	-0.8	-2.2
B-1	103	70.7	59.8	68.9	60.7	70.4	62.0	2.7	2.5	1.8	0.3	-0.9	-2.2
N-1	103	69.1	59.1	67.1	60.1	68.5	61.5	3.0	3.0	2.0	0.6	-1.0	-2.4
A-1	143	68.3	58.2	67.4	59.8	68.9	61.1	2.5	2.3	0.9	-0.6	-1.6	-2.9
O-2	61	74.2	64.1	71.0	65.3	72.5	66.8	4.4	4.4	3.2	1.7	-1.2	-2.7
C-2	66	74.8	64.2	72.2	65.4	73.8	66.8	3.8	3.8	2.6	1.0	-1.2	-2.6
D-2	69	74.6	64.0	72.1	65.3	73.6	66.7	3.8	3.7	2.5	1.0	-1.3	-2.7
G-2	75	74.7	64.7	71.6	66.1	73.2	67.5	4.5	4.3	3.1	1.5	-1.4	-2.8
H-2	77	74.5	64.7	71.4	65.9	73.0	67.3	4.3	4.1	3.1	1.5	-1.2	-2.6
I-2	78	74.2	64.5	71.3	65.7	72.8	67.1	4.1	4.0	2.9	1.4	-1.2	-2.6
B-2	84	73.8	63.8	71.3	64.9	72.9	66.3	3.6	3.4	2.5	0.9	-1.1	-2.5
F-2	84	74.0	63.8	71.2	65.0	72.8	66.3	4.0	3.7	2.8	1.2	-1.2	-2.5
M-2	92	72.3	62.4	69.4	63.6	70.9	65.0	4.1	4.0	2.9	1.4	-1.2	-2.6
L-2	94	72.6	62.8	69.7	63.9	71.2	65.3	4.0	3.9	2.9	1.4	-1.1	-2.5
J-2	95	73.1	63.3	70.2	64.5	71.8	65.9	4.1	3.9	2.9	1.3	-1.2	-2.6
K-2	99	72.7	62.9	69.8	64.1	71.4	65.4	4.1	3.8	2.9	1.3	-1.2	-2.5
B-2	103	72.7	62.3	70.5	63.9	72.1	65.3	3.8	3.6	2.2	0.6	-1.6	-3.0
N-2	103	71.3	61.8	68.4	62.9	69.9	64.3	4.0	3.9	2.9	1.4	-1.1	-2.5
A-2	143	71.0	60.4	68.9	62.4	70.5	63.7	4.1	3.8	2.1	0.5	-2.0	-3.3
							MEAN	3.7	3.6	2.7	1.2	-1.0	-2.4
							STD DEV	0.7	0.6	0.6	0.6	0.4	0.4
							MIN	1.8	1.8	0.9	-0.6	-2.0	-3.3
							MAX	4.5	4.4	3.6	2.2	-0.2	-1.6

Table 3-2 Comparison of predictions - TNM 1.0 verification problem.

Obs Dist (F)	TNM I.0 lawn REMEL 95		STAMINA @-.5 shielding = 0 FHWA 75		REMEL 95		Insertion Loss		W/O B		W/B		
	W/O B	W/B	W/O B	W/B	W/O B	W/B	TNM-S75	TNM-S95	TNM-S75	TNM-S95	TNM-S75	TNM-S95	
R8	55	69.8	62.4	72.9	65.0	71.3	63.5	-0.5	-0.4	-3.1	-1.5	-2.6	-1.1
R5	59	73.4	63.6	74.4	65.6	72.8	64.0	1.0	1.0	-1.0	0.6	-2.0	-0.4
R7	63	72.4	63.5	73.5	65.8	72.0	64.2	1.2	1.1	-1.1	0.4	-2.3	-0.7
R9	67	68.1	61.7	71.9	64.5	70.3	63.0	-1.0	-0.9	-3.8	-2.2	-2.8	-1.3
R10	67	66.6	61.1	71.3	64.1	69.7	62.6	-1.7	-1.6	-4.7	-3.1	-3.0	-1.5
R6	68	73.5	63.8	74.1	66.0	72.6	64.4	1.6	1.5	-0.6	0.9	-2.2	-0.6
R11	84	66.5	61.0	71.3	64.3	69.7	62.8	-1.5	-1.4	-4.8	-3.2	-3.3	-1.8
R12	85	66.7	61.0	71.4	64.6	69.8	63.0	-1.1	-1.1	-4.7	-3.1	-3.6	-2.0
R4	92	70.0	61.1	71.8	63.4	70.2	61.9	0.5	0.6	-1.8	-0.2	-2.3	-0.8
R13	118	65.4	60.4	70.1	64.3	68.6	62.8	-0.8	-0.8	-4.7	-3.2	-3.9	-2.4
R3	133	68.8	60.0	70.2	63.1	68.7	61.5	1.7	1.6	-1.4	0.1	-3.1	-1.5
R22	152	71.9	67.0	72.2	69.6	70.8	68.1	2.3	2.2	-0.3	1.1	-2.6	-1.1
R14	163	64.5	59.6	69.0	63.8	67.5	62.3	-0.3	-0.3	-4.5	-3.0	-4.2	-2.7
R23	166	72.6	68.0	72.9	69.7	71.5	68.2	1.4	1.3	-0.3	1.1	-1.7	-0.2
R24	200	71.2	66.2	71.4	68.3	70.0	66.7	1.9	1.7	-0.2	1.2	-2.1	-0.5
R21	214	68.0	61.8	70.1	66.6	68.6	65.0	2.7	2.6	-2.1	-0.6	-4.8	-3.2
R2	225	66.4	58.6	67.8	62.8	66.4	61.1	2.8	2.5	-1.4	0.0	-4.2	-2.5
R15	234	63.8	58.4	68.1	62.8	66.5	61.2	0.1	0.1	-4.3	-2.7	-4.4	-2.8
R25	254	69.4	63.9	70.2	66.9	68.8	65.3	2.2	2.0	-0.8	0.6	-3.0	-1.4
R20	271	66.1	59.5	68.9	64.6	67.4	63.0	2.3	2.2	-2.8	-1.3	-5.1	-3.5
R1	302	64.6	57.6	66.4	62.3	64.9	60.6	2.9	2.7	-1.8	-0.3	-4.7	-3.0
R16	324	62.9	57.1	67.0	61.8	65.4	60.2	0.6	0.6	-4.1	-2.5	-4.7	-3.1
R19	328	64.5	58.0	68.0	63.1	66.4	61.5	1.6	1.6	-3.5	-1.9	-5.1	-3.5
R18	383	63.1	56.9	67.0	62.0	65.4	60.4	1.2	1.2	-3.9	-2.3	-5.1	-3.5
R26	390	66.2	60.2	67.7	64.6	66.3	63.0	2.9	2.7	-1.5	-0.1	-4.4	-2.8
R17	446	61.0	55.5	65.5	60.4	63.8	58.9	0.4	0.6	-4.5	-2.8	-4.9	-3.4
R27	513	64.1	58.2	65.9	63.2	64.6	61.5	3.2	2.8	-1.8	-0.5	-5.0	-3.3
							MEAN	1.02	0.97	-2.57	-1.06	-3.60	-2.02
							STD DEV	1.47	1.36	1.63	1.57	1.14	1.12
							MIN	-1.70	-1.60	-4.80	-3.20	-5.10	-3.50
							MAX	3.20	2.80	-0.20	1.20	-1.70	-0.20

Table 3-3 Comparison of predictions - I-78 in Pennsylvania.

Obs Dist Ft	TNM 1.0 REMEL 95		STAMINA FHWA 75		STAMINA REMEL 95		Insertion Loss			w/o B			w/B		
	w/o B	w/B	w/o B	w/B	w/o B	w/B	TNM-S75	TNM-S95	TNM-S95	TNM-S75	TNM-S95	TNM-S75	TNM-S95	TNM-S75	TNM-S95
A4	33	75.2	66.2	76.6	70.0	75.5	68.7	2.4	2.2	-1.4	-0.3	-3.8	-2.5		
A5	35	75.4	66.3	76.9	70.0	76.0	68.7	2.2	1.8	-1.5	-0.6	-3.7	-2.4		
A3	36	75.1	66.8	76.5	71.0	75.3	69.6	2.8	2.6	-1.4	-0.2	-4.2	-2.8		
A2	42	75.3	68.1	75.9	71.6	74.7	70.3	2.9	2.8	-0.6	0.6	-3.5	-2.2		
A6	55	74.5	64.6	75.4	68.2	74.4	66.8	2.7	2.3	-0.9	0.1	-3.6	-2.2		
A1	56	74.0	67.3	74.7	70.7	73.5	69.4	2.7	2.6	-0.7	0.5	-3.4	-2.1		
A7	76	73.6	63.9	74.4	67.8	73.4	66.4	3.1	2.7	-0.8	0.2	-3.9	-2.5		
B4	33	77.0	69.5	76.9	73.2	76.0	71.9	3.8	3.4	0.1	1.0	-3.7	-2.4		
B5	35	77.1	69.4	77.0	73.1	76.2	71.7	3.8	3.2	0.1	0.9	-3.7	-2.3		
B3	36	76.9	70.6	76.7	73.3	75.8	72.1	2.9	2.6	0.2	1.1	-2.7	-1.5		
B2	42	77.3	72.0	76.2	73.3	75.2	72.1	2.4	2.2	1.1	2.1	-1.3	-0.1		
B6	55	75.3	66.5	75.6	70.6	74.8	69.2	3.8	3.2	-0.3	0.5	-4.1	-2.7		
B1	56	75.7	70.4	75.1	72.2	74.1	70.9	2.4	2.1	0.6	1.6	-1.8	-0.5		
B7	76	74.1	65.9	74.5	69.7	73.6	68.2	3.4	2.8	-0.4	0.5	-3.8	-2.3		
MEAN							2.95	2.61	-0.42	0.57	-3.37	-2.04			
STD DEV							0.56	0.46	0.78	0.74	0.85	0.80			
MIN							2.20	1.80	-1.50	-0.60	-4.20	-2.80			
MAX							3.80	3.40	1.10	2.10	-1.30	-0.10			

Table 3-4 Comparison of predictions - Route 59 in Streamwood, IL.

Obs Dist (F)	TNM 1.0 REMEL 95		STAMINA FHWA 75		STAMINA REMEL 95		Insertion Loss		w/o B		w/ B							
	w/o B	w/ B	w/o B	w/ B	w/o B	w/ B	TNM-S75	TNM-S95	TNM-S75	TNM-S95	TNM-S75	TNM-S95						
rec10	24	70.5	58.1	71.6	60.0	70.5	58.8	0.8	0.7	-1.1	0.0	-1.9	-0.7					
rec11	24	71.7	58.7	73.4	61.9	72.4	60.8	1.5	1.4	-1.7	-0.7	-3.2	-2.1					
rec7	54	67.5	56.8	69.0	59.8	67.9	58.6	1.5	1.4	-1.5	-0.4	-3.0	-1.8					
rec8	62	67.5	57.4	69.2	60.6	68.1	59.4	1.5	1.4	-1.7	-0.6	-3.2	-2.0					
rec6	67	68.0	56.5	67.9	59.9	66.8	58.6	3.5	3.3	0.1	1.2	-3.4	-2.1					
rec9	80	68.6	57.6	69.0	61.1	67.9	59.9	3.1	3.0	-0.4	0.7	-3.5	-2.3					
rec5	97	66.9	56.4	67.0	60.0	65.9	58.7	3.5	3.3	-0.1	1.0	-3.6	-2.3					
rec4	154	65.7	56.3	65.9	60.1	64.8	58.9	3.6	3.5	-0.2	0.9	-3.8	-2.6					
rec3	207	65.1	56.3	65.1	60.1	64.0	58.8	3.8	3.6	0.0	1.1	-3.8	-2.5					
rec2	252	64.3	56.2	64.3	60.0	63.3	58.7	3.8	3.5	0.0	1.0	-3.8	-2.5					
rec1	305	63.1	56.0	63.0	59.7	62.0	58.4	3.8	3.5	0.1	1.1	-3.7	-2.4					
MEAN													2.76	2.60	-0.59	0.48	-3.35	-2.12
STD DEV													1.17	1.12	0.75	0.75	0.56	0.53
MIN													0.80	0.70	-1.70	-0.70	-3.80	-2.60
MAX													3.80	3.60	0.10	1.20	-1.90	-0.70

Table 3-5 Comparison of predictions - I-355 North of Army Trail in Addison, IL.

STAMINA analyses consistently over-predict the traffic noise relative to TNM. The updated vehicle emissions in STAMINA produce a larger over-prediction that may be due to the multiple barriers between the receivers and roadways that STAMINA cannot analyze. Also, the traffic is predominately automobiles with a relatively low volume of medium and heavy trucks. The on-ramp was modeled in TNM, but it had relatively little effect because of the low traffic volume on the ramp.

I-78 in Pennsylvania

The I-78 analysis (Table 3-3) shows the largest scattering of the differences between the three analyses. The standard deviations for the differences ranged from 1.12 to 1.63 dBA. Also there were a significant number (about 40%) of the differences more than one standard deviation from the mean. The IL mean differences were both about 1.0 dBA between the two STAMINA analyses and TNM. The differences for both "without barrier" and "with barrier" conditions show that the STAMINA models over-predicted the noise relative to TNM. The updated vehicle noise coefficients in STAMINA reduced the mean over-prediction by about 1.5 dBA without the barrier and with the barrier.

The I-78 example had an entrance ramp that was modeled in TNM. The ramp modeling should have increased the noise emissions for the vehicles on the ramp. Overall, there was only a small change (on the order of 1 dBA) in the TNM predicted noise levels. The receivers near the ramp (R1, R2, R3, and R4) should have been the most significantly affected. However, no noticeable trend was found between these receivers and the other receivers.

Route 59 and I-355 in Illinois

The two Illinois examples, Route 59 and I-355 (Tables 3-4 and 3-5) in general show similar trends. The mean IL differences are similar between the two STAMINA models and TNM, with STAMINA under-predictions of 2.60 and 2.95 dBA. Without the barrier, the two STAMINA analyses show small mean difference of about 0.5 dBA compared to the TNM model. With the barrier, the original STAMINA over-predicts the mean noise by 3.4 dBA relative to TNM while the updated STAMINA over-predicts by 2.1 dBA. Therefore, with the barrier, there is a mean improvement of 1.3 dBA using the updated vehicle emission coefficients in STAMINA relative to TNM.

Even though these two analyses show similar mean differences, they represent very different site geometries. The Route 59 analysis was fairly simple with one main roadway that is on-grade with the receivers. However, the I-355 analysis included two intersecting roads with an entrance ramp. The main highway was approximately on-grade with the receivers. The most notable similarity was a similar traffic mix, even though the volumes and speeds were different.

The I-355 example (Table 3-5) is the only one of this set that shows a clear relation between the noise differences and the distance of the receivers behind the barrier. This might relate to the fact that the receivers on the left side are furthest from the barrier and they are the ones that are most highly affected by the adjacent ramp.

3.2.4 Discussion

The four examples all show that the updated vehicle emissions coefficients reduce the difference between STAMINA and TNM. All the test examples show that updating the vehicle noise emission coefficients in STAMINA improves noise predictions relative to TNM. On average, this reduces the difference between the STAMINA and TNM noise predictions by about 1.5 dBA. However, it is also evident that just updating the vehicle noise coefficients does not completely correct the differences between STAMINA and TNM.

The IL differences suggest that there are still significant differences between TNM and STAMINA even after updating the vehicle noise coefficients. The mean IL difference ranges from 0.97 to 3.7 dBA for the test problems. In all four cases there is a consistent mean IL difference between the two STAMINA versions relative to TNM. This suggests that updating the vehicle emission values in STAMINA does not significantly impact the IL prediction. Therefore, without changing the diffraction model in STAMINA, the predicted IL will not be significantly changed. All the test examples show that STAMINA under-predicted the IL relative to TNM by 1 to 3.6 dBA.

By updating the vehicle noise coefficients in STAMINA, the noise level predictions are improved, but there is little to no change to IL predictions. The decision to recommend a noise barrier for a new highway project (Type I) depends on both the noise level and the ability to achieve a minimum IL. Improving only the vehicle noise levels in STAMINA does not completely correct the deficiencies, but provides a partial fix that is potentially useful.

3.2.5 Conclusions and Recommendations

The FHWA has indicated that TNM will replace STAMINA. Yet, some transition period is required for users to fully accept TNM. TNM has the potential to provide more realistic predictions, but the current runtimes along with software bugs and numerical problems are unacceptable. STAMINA, which has a large community of experienced users, might continue to be used to analyze sites with relatively simple geometry. Updating the vehicle emission coefficients can extend the usefulness of STAMINA. Both noise prediction programs could be used in the transition period. There is room for improvement of both analyses. The acoustic research community should consider working on improving both models, instead of abandoning one. The TNM model offers precision and graphical interface at the cost of run time and complexity of input. On the other hand, STAMINA is relatively simple and runs quickly but needs to be more user-friendly.

To allow multiple noise prediction models for noise studies, a clear recommendation is needed to indicate when each is acceptable and unacceptable. To develop this recommendation, the acoustic research community should scrutinize and test each program. This should include comparing both analysis models against appropriate field measurements. Then based on these studies, the FHWA, state DOTs, and the research community should draft appropriate recommendations or guidelines for use of each program or other noise prediction means.

The experience with STAMINA and its over-prediction of traffic noise levels indicates that the 1995 REMEL database should be periodically updated and periodically checked for

validity. By regularly updating the REMEL database, a new potential problem arises of which version of the database is being used for the noise study. This potential problem should be discussed soon so that an appropriate solution can be implemented before the traffic noise data needs updating again. The solution might involve providing the REMEL database on the World Wide Web so end-users can use the latest vehicle emission data.

3.3 Field Measurements

One of the tasks to evaluate the FHWA traffic noise prediction programs was to compare the predictions to a series of field measurements. This part of the study was carried out in four stages: site selection, initial practice runs, field measurements, and analysis.

3.3.1 Traffic Noise Measurement Protocol

The traffic noise protocol was developed based on the FHWA traffic noise measurement procedure [Lee and Fleming, 1996] and the project objectives. The protocol was formed as a series of tasks and specific instructions where appropriate. The protocol was practiced and refined to ensure workability and appropriate order of steps.

The measurement team consisted of five crewmembers, although a three-person crew could have been used. The larger team minimized errors as well as the pre- and post-test time. The task assignments included measurement coordinator, two operators for the Sound Level Meters (SLM), a video operator, and a site surveyor/photographer.

Equipment List

- Two - Sound Level Meters (SLM) Type 1 Bruel & Kjaer 2236 with wind screens,
- Acoustic Calibrator - 94 dB at 1K Hz - Bruel & Kjaer 4231
- Pink noise generator and adapters
- Dummy microphone
- Two- Microphone extension cables for SLM, at least 10 m
- Three - Tripods for SLM and Microphones
- Total Station and tripod
- Video camera, remote monitor, and clamp bracket
- Digital camera
- Weather Station - Davis Instruments
- Laptop computer and interface cables to connect to SLM and Weather Station
- Ladders and clamp with microphone holder for the reference microphone

The traffic noise measurement protocol is as follows

- Initial calibration according to FHWA-PD-96-046 [Lee and Fleming, 1996]. Calibrate each SLM with acoustic calibration source. Record the noise floor with a dummy microphone. Record the spectrum response with a pink noise generator. The calibration was done in a hotel room before traveling to the sites.
- Site preparation - Locate receiver locations with a Total Station, surveying equipment. Check SLM calibration, set-up reference microphone above the wall (Figure 3-8) and the



Figure 3-8 Reference microphone above the wall



Figure 3-9 Microphone with windscreen.

other SLM at the first receiver location. Both SLMs have at least a 10 m extension cable between the SLM and its microphone. Each microphone is oriented vertically in a grazing configuration with a windscreen (Figure 3-9). Clamp the video camera to the top of the barrier wall to record traffic volume (Figure 3-10). Set-up the weather station to record wind speed, wind direction, temperature, relative humidity, and barometric pressure (Figure 3-11). The weather station is located so that it does not interfere with the noise measurements and yet captures the environmental conditions.

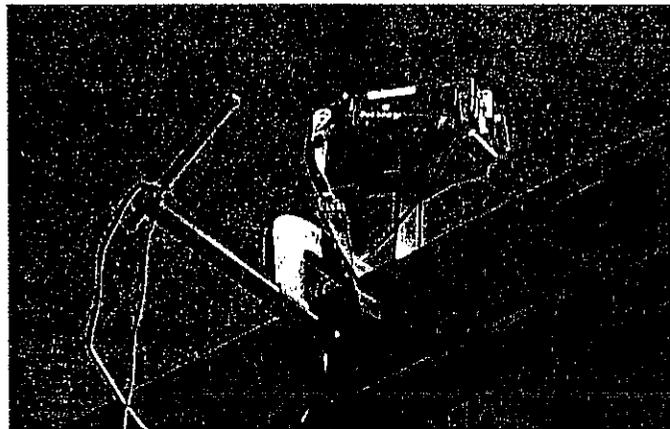


Figure 3-10 Video camera to record traffic volume.

- Record traffic noise - Simultaneously record the traffic noise at the reference and one of the receiver locations. Record 6 two-minute samples of integrated noise - Leq. The B&K SLM store Leq at one-minute intervals instead of two-minutes, so 12 one-minute samples are taken. The SLM's memory contain the whole day's measurements is downloaded to a laptop computer at the end of the day. The SLM operator at the

reference location uses hand signals to indicate the start and end of the measurement period. The measurements are repeated for each receiver location of 25, 50, 100, and 200 ft. If measurements take over one hour, re-check the SLM calibration. In all cases, the measurement did not exceed one hour. The video operator kept records of cloud cover and unusual non-traffic noises.

- Survey of sites - The Total Station is used to survey the significant site geometric features such as berms, ditches, or paved areas for use in prediction analyses. The sites are photographed for documentation.
- Post Measurement - Re-check SLM calibration with extension cable still connecting microphone to SLM. Repack equipment and pick up any debris from site. Verify that records are complete.



Figure 3-11 Weather station.

3.3.2 Site Selection

The site selection started with the development of site criteria. The criteria were that each site should have

1. A noise barrier without significant defects
2. Free flowing traffic with moderate to high traffic volume (greater than 1000 vph).
3. A line for observers up to 200 ft from the barrier that are all at least 50 ft from any prominent obstruction.
4. Traffic noise is the only significant local noise source.

To have consistently high traffic volumes, all the sites considered were in the Chicago metropolitan area. Candidate sites in IDOT District 1 were suggested by Michelle Mahoney and Mitch Rogers, who provided a drive-by of the sites. Three candidate sites were selected in District 1, but one was rejected by the project Technical Review Panel due to the complexity of the highways and the possibility of high background noise levels. Sites along the Illinois Tollway were screened by a helicopter fly-over arranged by John C. Herne. The Tollway sites were visited at ground level and evaluated when the District 1 sites were measured.

Four sites were selected and noise measurements were made in two trips (July 23, 1998 and August 19, 1998). Traffic noise measurement at each site required about half a day to complete. The sites are described below.

Farmwood Park, Addison - I290 (7-23-1998)

This site is a local park in a residential area and is also used as a storm water retention area during the rainy season (Figure 3-12). It is on the south side of I-290, opposite from the Songbird Slough Forest Preserve and east of the intersection of I-290 and Highway 53. The barrier was wooden on an earthen berm. The site background noise was very low, except for some airplane flyovers late morning.

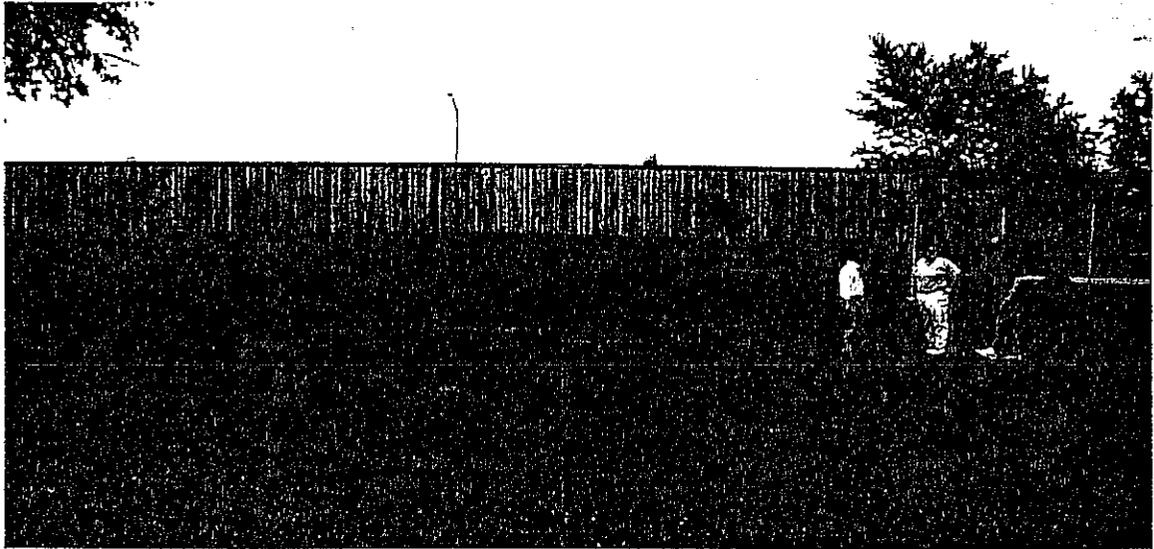


Figure 3-12 Farmwood Park, Addison - I-290.

Maple Street, Clarendon Hills - Route 83 south of Ogden (RT 34) (7-23-1998)

This site was along a residential street perpendicular to the barrier wall. The site was west of Route 83, Robert Kingery Highway, and south of Route 34, Ogden. Route 83 is a surface street with a depressed section at Chicago Ave., south of the site. The noise barrier runs from Chicago Ave. to south of Ogden, with a residential street run behind the barrier. At the measurement site, the barrier was corrugated concrete panels (Figure 3-13). Further north, the barrier was wooden. The video camera was located on the wooden barrier (Figure 3-14). A low level of traffic on the surface street contributed a moderate level of background noise.

The measurement protocol was modified at the Maple street site to eliminate the 25 ft observer location, which would have been in the middle of the local surface street. The study team decided that it would be impractical to stop traffic for the 12 minute measurement period.

Martin Park, Hickory Hills - I-294 (8-19-1998)

This Tollway site was at the corner of a small community park on the west side of I-294, between Route 12/20 (96th Street) and 87th Street (Figure 3-15). The park included two baseball diamonds, a small pond with tree cover, and play ground equipment. The noise barrier was precast concrete panels with the appearance of block construction and concrete columns. There was a drainage ditch directly behind the barrier and chain-link fence. To avoid trees and a gazebo, the line of receiver locations crossed an asphalt parking area.



Figure 3-13 Corrugated concrete barrier at Maple Street.



Figure 3-14 Wooden barrier at video camera location.

This site had numerous local noise sources that were not apparent when the site was initially selected. On the day scheduled for the measurements, a backhoe started digging the basement for a structure. The construction site was approximately 500 feet north of the reference location (Figure 3-16). In addition, there were house construction noises from South of the park, airplane flyovers, and a small number of children using the play ground (about 400 ft from any receiver location). Because of concerns over the background noise, the 50 ft and 100 ft observer measurements were repeated. The 25 ft and 200 ft locations

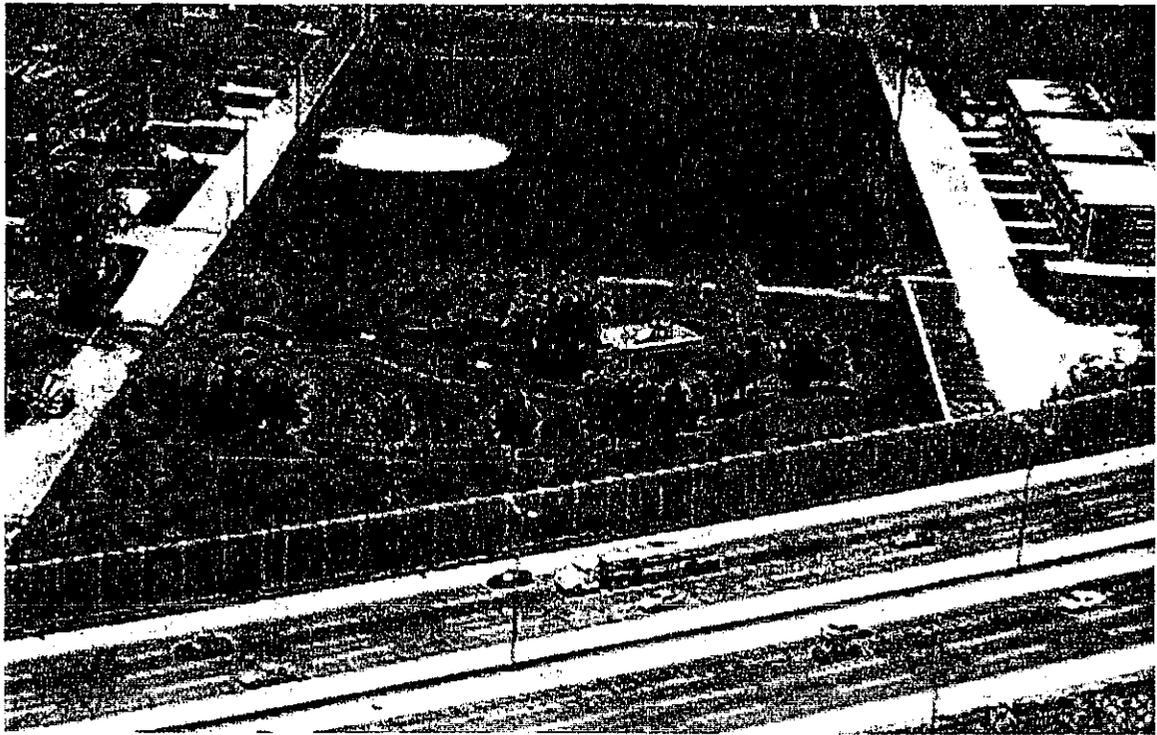


Figure 3-15 Martin Park ariel view.

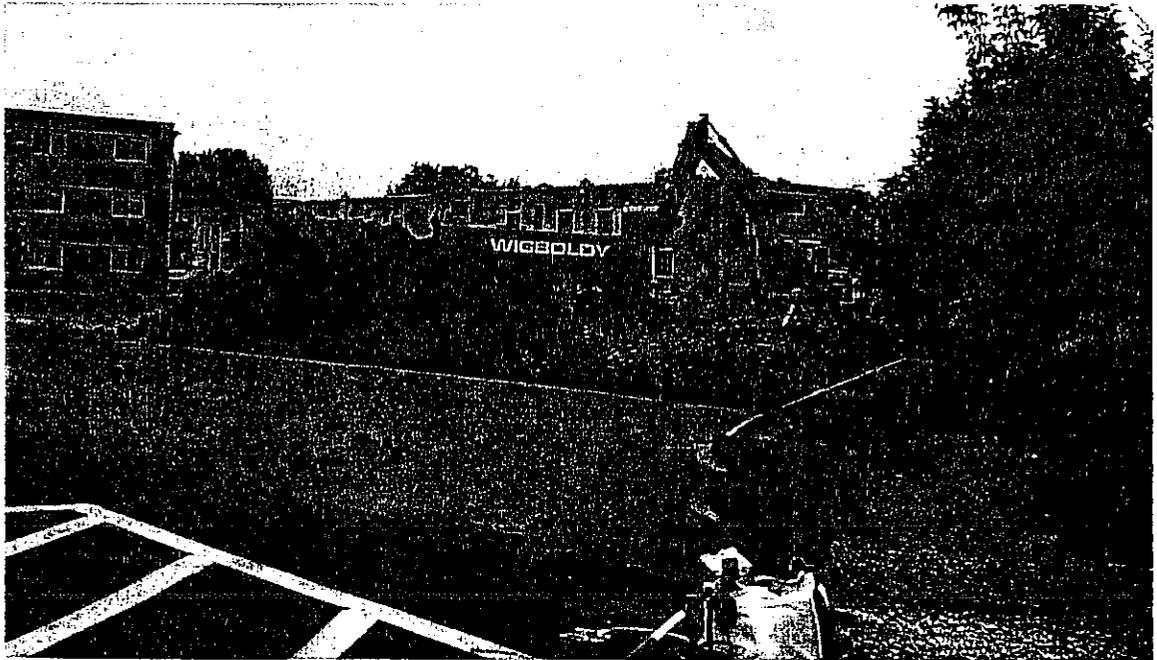


Figure 3-16 Backhoe operating near Martin Park site.

were not repeated because the backhoe was not operating during these measurement intervals.

Hinsdale - I-294 North of 55th Street (8-19-1998)

This site was a strip of property owned by the Toll Highway Authority with moderate tree

cover. The site was on the west side of I-294, just north of 55th Street (Figure 3-17). The barrier was cast concrete panels and columns similar to those at the Martin Park site. Directly behind the barrier were shrubs and vegetation. Also behind most of the barrier were earthen berms with a height of approximately 5 ft (Figure 3-18). The line of observation sites ran between a pair of berms. The 200 ft observer location was across a residential street, so there might have been slightly higher background noise this location due to occasional residential traffic.



Figure 3-17 Hinsdale - I-290 north of 55th street.



Figure 3-18 Earthen berms at Hinsdale site.

3.3.3 Noise Measurement Results

Each measurement site was modeled in both STAMINA 2.0 and FHWA TNM 1.0 based on the road site plans. The noise level predictions were compared to the average measured noise levels using $\pm 2 \sigma$ (standard deviations) for a 5% α , or 95% confidence level.

The analysis files were created using University of Louisville's Microstation procedure to generate files in STAMINA format [Cohn and Harris, 1996]. The plan-view of each roadway and its barriers were drawn in AutoCAD 13 and then the STAMINA analysis files were created by digitizing the roads and barriers every 200 ft. Elevations were input to the nearest 0.1 ft. This STAMINA data file was also used as input to the FHWA TNM 1.0 program.

Traffic volumes were determined for each travel direction by counting vehicles from the videotape. Counts were done for a two-minute interval selected at random during each 12-minute measurement interval. All the counts for each site were averaged for use in the analyses. The counts were accomplished using a custom built counting system consisting of a box with switches attached to a PLC (Programmable Logic Controller - ZWorld Tiny Giant). The PLC counted button presses and timed the counting interval. The counting operator held a small box with three momentary contact buttons (normally open) and a toggle switch to signal the start and stop of the measurement. The three push buttons were for the

7/23/98		Automobile		Med. Truck		Heavy Truck	
		far ->	near ->	far ->	near ->	far ->	near ->
Farmwood Park	25ft	3090	2551	150	330	420	450
	50ft	3810	3030	180	330	60	540
	100ft	3060	3180	150	300	240	270
	200ft	3030	2700	150	300	240	450
AVG		3248	2865	158	315	240	428
Maple Street		25ft	—	—	—	—	—
		50ft	2790	1800	90	90	60
		100ft	2760	1830	90	90	0
		200ft	2730	1860	0	150	60
AVG		2760	1830	60	110	60	60
8/19/98		Automobile		Medium Truck		Heavy Truck	
		far ->	near ->	far ->	near ->	far ->	near ->
Martin Park	25ft	2880	2310	210	360	960	330
	50ft-1	3030	2310	60	60	750	540
	100ft-1	2400	3180	120	270	630	1110
	200ft	2820	2460	90	120	600	870
	50ft-2	3060	3150	210	150	900	750
	100ft-2	3150	2520	120	240	660	1110
AVG 4 lanes		2890	2655	135	200	750	785
AVG /2 lanes		1445	1328	68	100	375	393
Hinsdale		25ft	4980	3690	270	180	660
		50ft	5580	3780	60	240	900
		100ft	6420	4230	150	60	1140
		200ft	7200	3540	240	90	930
AVG 4 lanes		6045	3810	180	143	908	623
AVG /2 lanes		3023	1905	90	71	454	311

Table 3-6 Traffic volumes.

three vehicle types of automobiles, medium trucks, and heavy trucks. The resulting traffic volumes are summarized in Table 3-6.

TNM has no restriction on traffic speed, but STAMINA limits the traffic speed to a maximum of 65 mph. To overcome this limitation, the vehicle noise coefficients were fit to a reduced speed function. New STAMINA vehicle emission coefficients were determined so that the analysis speeds could be reduced by 10 mph, so that they would not exceed the program speed limit. The fitting was done in essentially the same way as was used to fit the TNM REMEL to the STAMINA equations (Section 3.2). Table 3-7 shows the offset STAMINA vehicle noise emission coefficients for both the original 1975 FHWA and the 1995 updated values. To use these coefficients in STAMINA, the traffic volumes should be adjusted by a factor of 0.8571 based on vehicle speed of 70 mph reduced to 60 mph (Equation 1).

1975 STAMINA REMEL offset by 10 mph

	C0	C1	σ	Corr. Coef.
Automobiles	20.44	30.64	2.50	0.999
Medium Trucks	36.00	27.31	3.37	0.999
Heavy Trucks	52.73	19.78	2.84	0.999

1995 TNM REMEL fit to STAMINA and offset by 10 mph

	C0	C1	σ	Corr. Coef.
Automobiles	17.91	30.64	2.62	0.999
Medium Trucks	37.74	19.78	2.90	0.997
Heavy Trucks	52.73	24.85	2.45	0.995

Table 3-7 Off-set STAMINA REMEL coefficients.

The predicted and measured noise levels for each site are compared. The analysis configuration for each site is depicted by the plan view from TNM, where the black lines with single arrows represent roadways, the red lines with double arrow heads represent barriers, the small squares are receivers, the green lines are terrain lines, and the areas enclosed with black lines are ground zones (where the noise attenuation rate is different from the default (lawn)). The predicted and measured noise levels are compared in bar charts. The predictions were done for two speeds that bracket the expected traffic speed to account for variations in traffic speed during the measurement interval. The measured noise level included a 95% confidence interval error bar. To further highlight statistical confidence levels, another series of plots shows the differences between the predicted and measured noise levels and the 95% confidence levels.

Farmwood Park, Addison - I290 (7-23-1998)

The Farmwood Park site is shown in Figure 3-19 and the predicted and measured noise levels are shown in Figures 3-20 and 3-21. The two charts show three prediction analyses: STAMINA 2.0, STAMINA with updated REMEL (STAM 95), and TNM 1.0 at speeds of both 65 mph and 70 mph, as well as the measured traffic noise at all receiver locations. At the reference location, only the two TNM predictions are within the 95% confidence limits. At the 25 and 50 ft receiver locations, both TNM and the 65 mph updated STAMINA analyses are within the 95% confidence limits. At the 100 ft receiver location, none of the

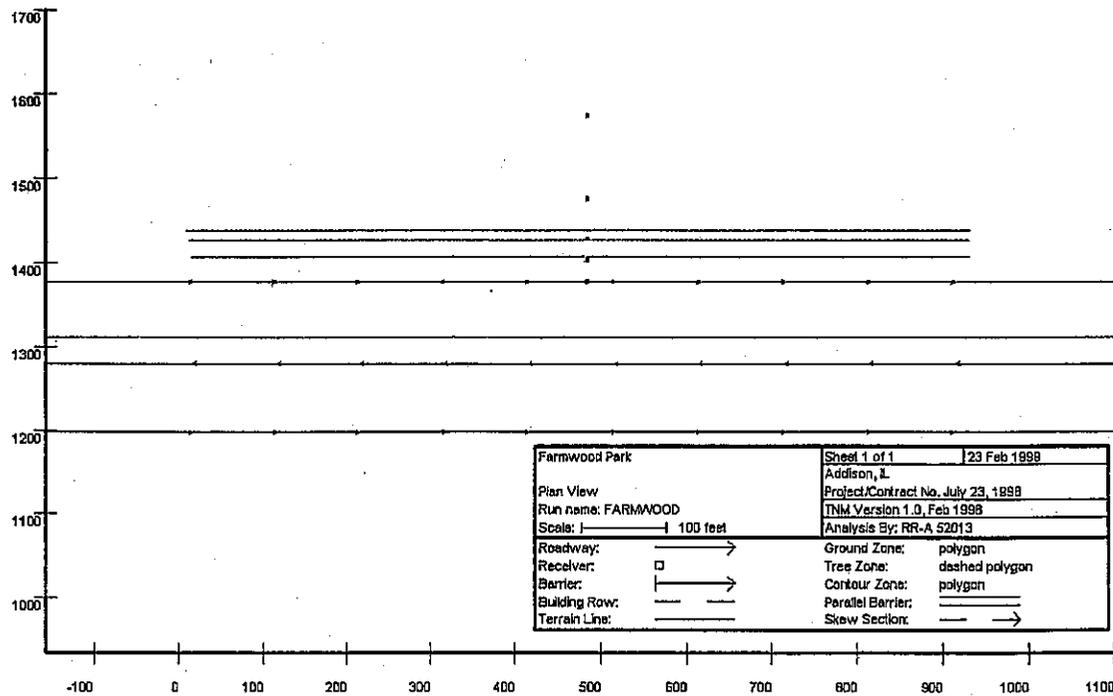


Figure 3-19 Farmwood Park Analysis.

Farmwood Park 7-23-98

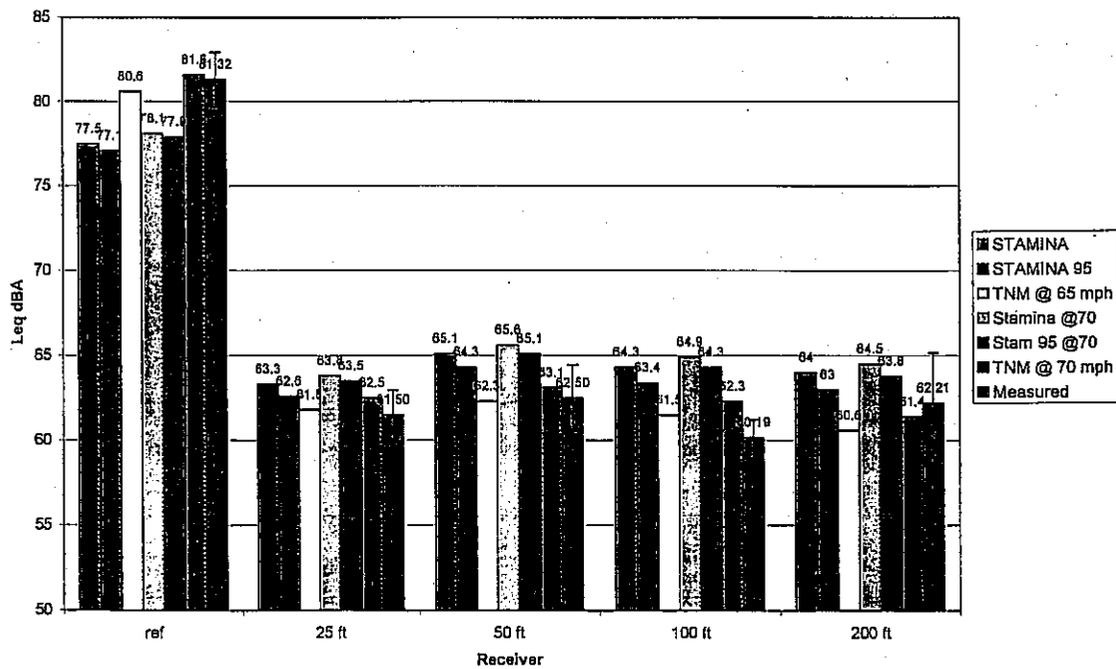


Figure 3-20 Comparison of predicted and measured noise levels - Farmwood Park.

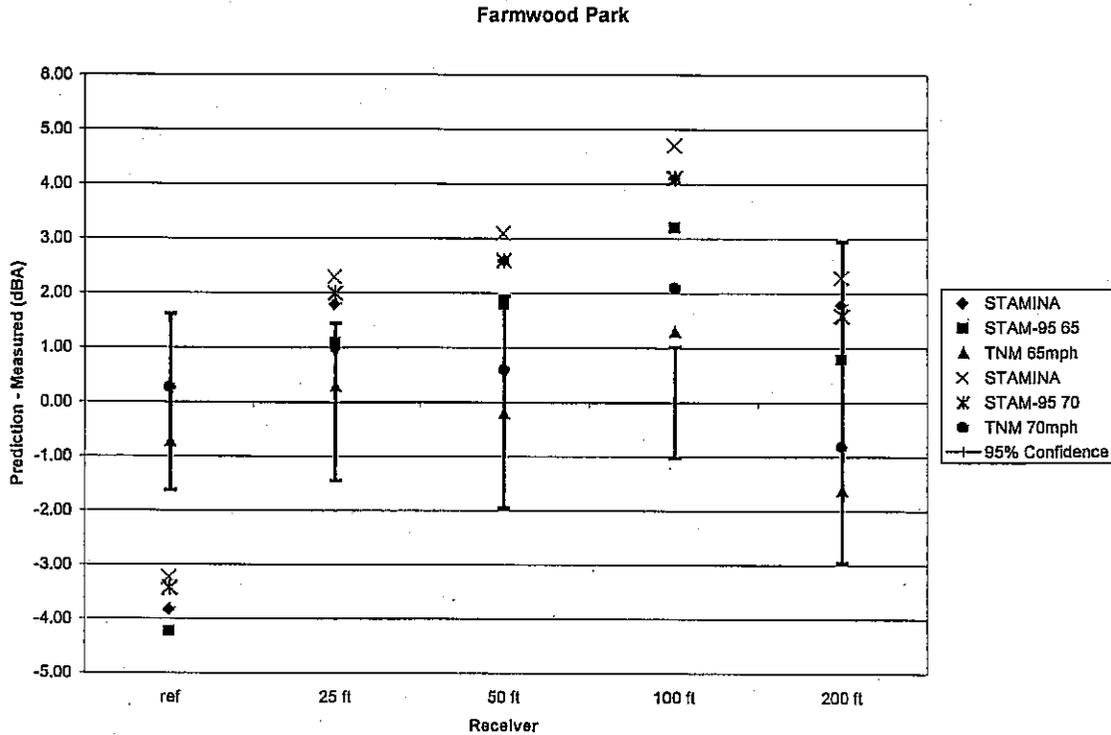


Figure 3-21 Differences between predicted and measured noise - Farmwood Park.

analyses are within the 95% confidence limit. The TNM prediction at 65 mph is closest to the confidence limit, being within 0.5 dBA. At 200 ft, all of the analyses are within the 95% confidence limit. Overall, only the TNM model agrees well at all receiver locations for this site. The reference location shows the greatest difference between measured and TNM predicted noise levels.

Maple Street, Clarendon Hills - Route 83 south of Ogden (RT 34) (7-23-1998)

The Maple Street TNM analysis included ground zones to represent the paved streets behind the barrier (Figure 3-22). The comparisons of predicted and measured noises are shown in Figures 3-23 and 3-24. Similar to the previous site, three prediction analyses are shown at two speeds -- 55 mph and 60 mph -- as well as the measured traffic noise at each receiver location. In addition, there are two additional bars at each receiver for TNM analyses that included a house row (60% shielding). The house row shielding only affected the 100 and 200 ft receiver locations.

At the reference location, only the TNM analyses are within the confidence limits. At the 50, 100, and 200 ft receivers, all but two bars (both TNM analyses) are within the confidence limit. Introducing the house row in TNM corrects the TNM over-prediction at 100 ft. Even though all the predictions at 200 ft are within the confidence limits, the TNM predictions with the house row are numerically closer to the measured values. At this site the two variations of STAMINA produce nearly identical results; the maximum difference is 0.4 dBA.

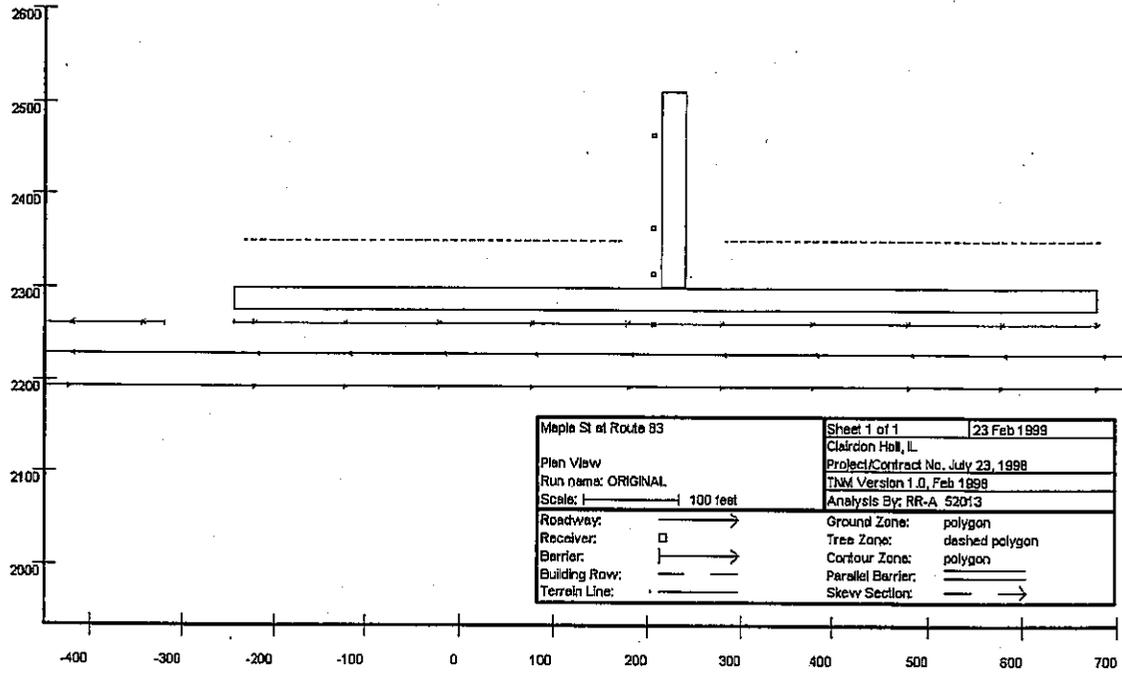


Figure 3-22 Maple Street Analysis.

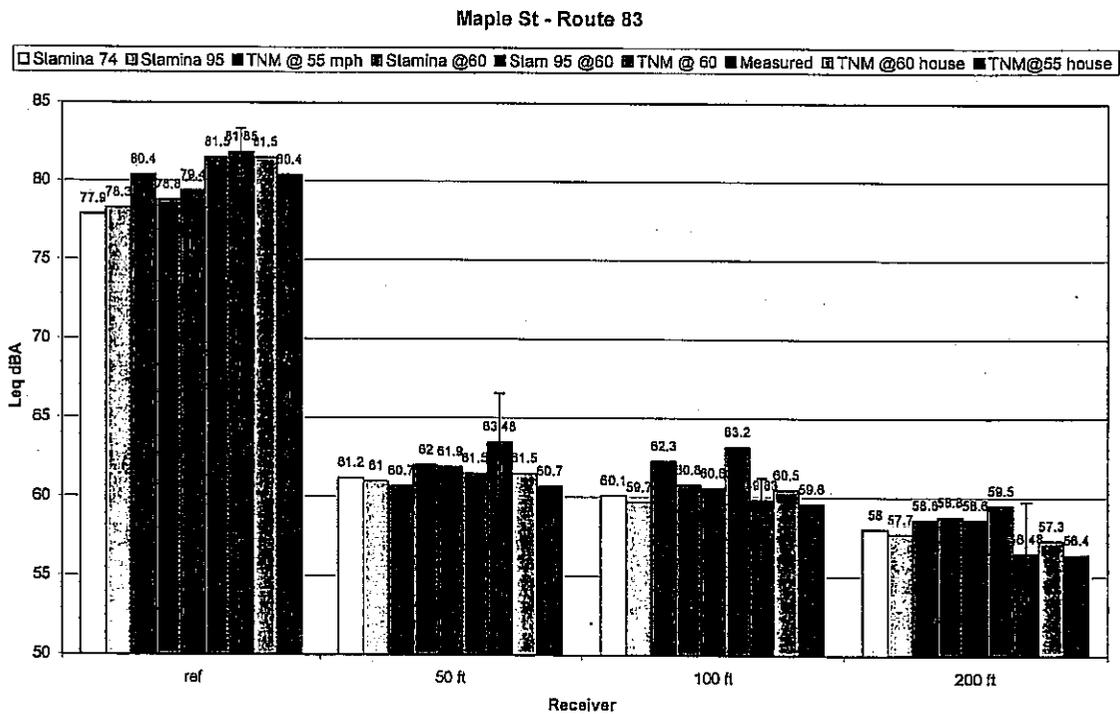


Figure 3-23 Comparison of predicted and measured noise levels - Maple Street.

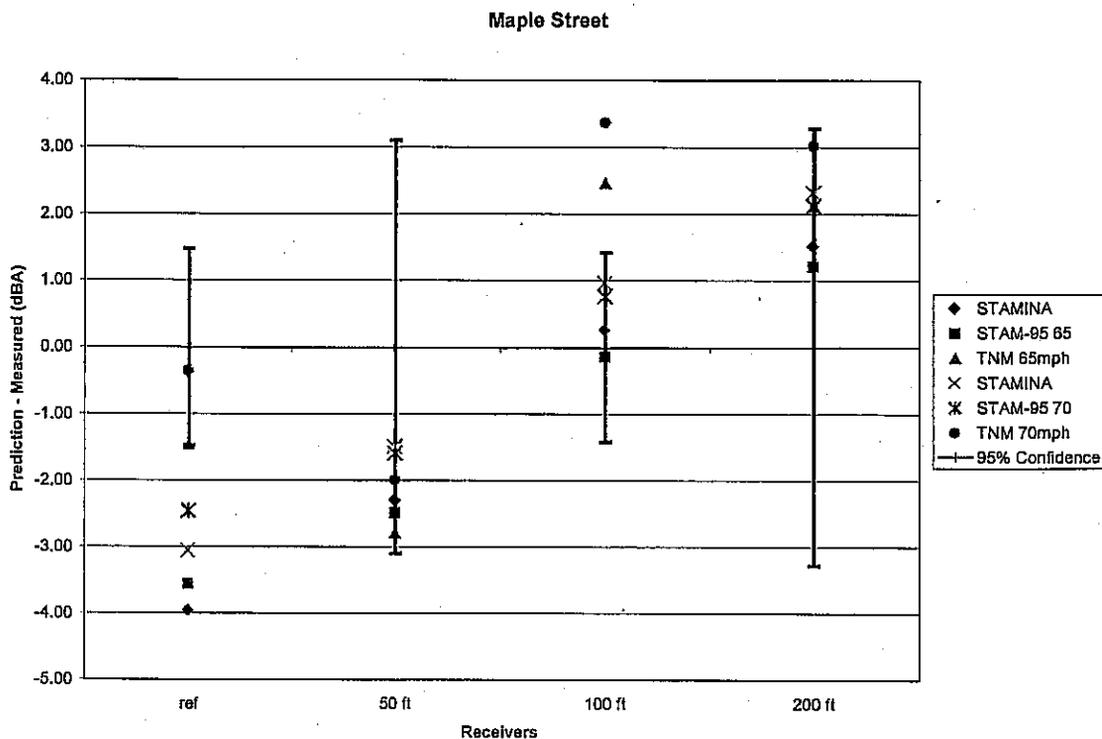


Figure 3-24 Differences between predicted and measured noise - Maple Street.

Martin Park, Hickory Hills - I-294 (8-19-1998)

The Martin Park TNM analysis includes ground zones and terrain lines as shown in Figure 3-25. The comparison of the predicted and measured noise levels are shown in Figures 3-26 and 3-27. The charts for this site are organized identically to Farmwood Park with three prediction analyses at speeds of 65 mph and 70 mph, along with the measured traffic noise. All but two bars are within the 95% confidence limits. The two TNM predictions at the reference location are not within the confidence limit. Even though all the analyses at the receiver locations are within the confidence limits, the original STAMINA shows the largest error, the updated STAMINA shows significant improvement, and the TNM analysis shows the smallest error.

In general, this site had the largest statistical standard deviations of all the measured sites. This is believed to be due to the non-traffic background noise sources near this site. These background noises should have caused the measured noise to be larger than predictions. Yet the majority of the predictions are higher than the measured noise levels.

At the reference location, all but one prediction is greater than the measurement, which is contrary to the trend from the other sites, where the STAMINA analyses under-predicted the measured noise.

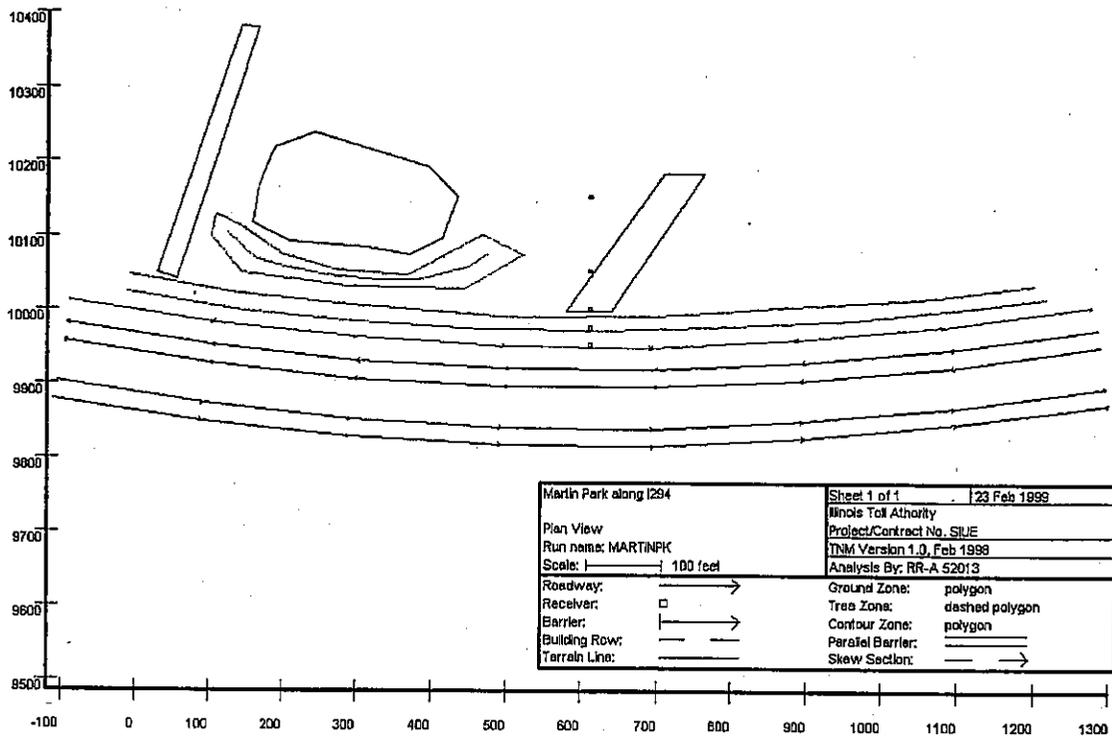


Figure 3-25 Martin Park analysis.

Martin Park I-294

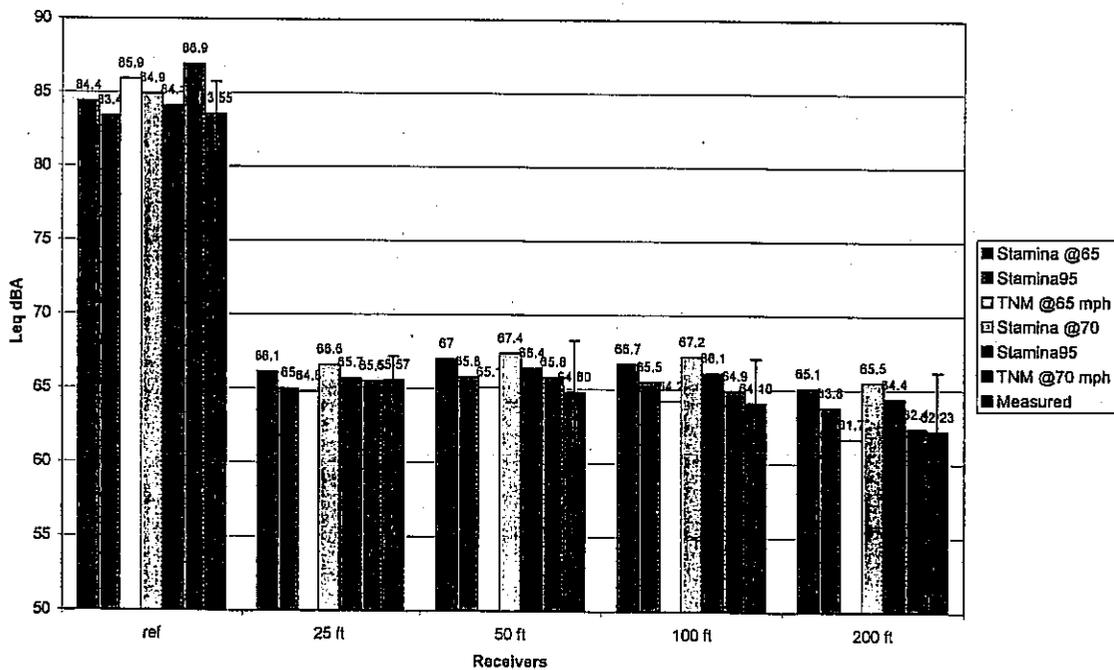


Figure 3-26 Comparison of predicted and measured noise levels - Martin Park.

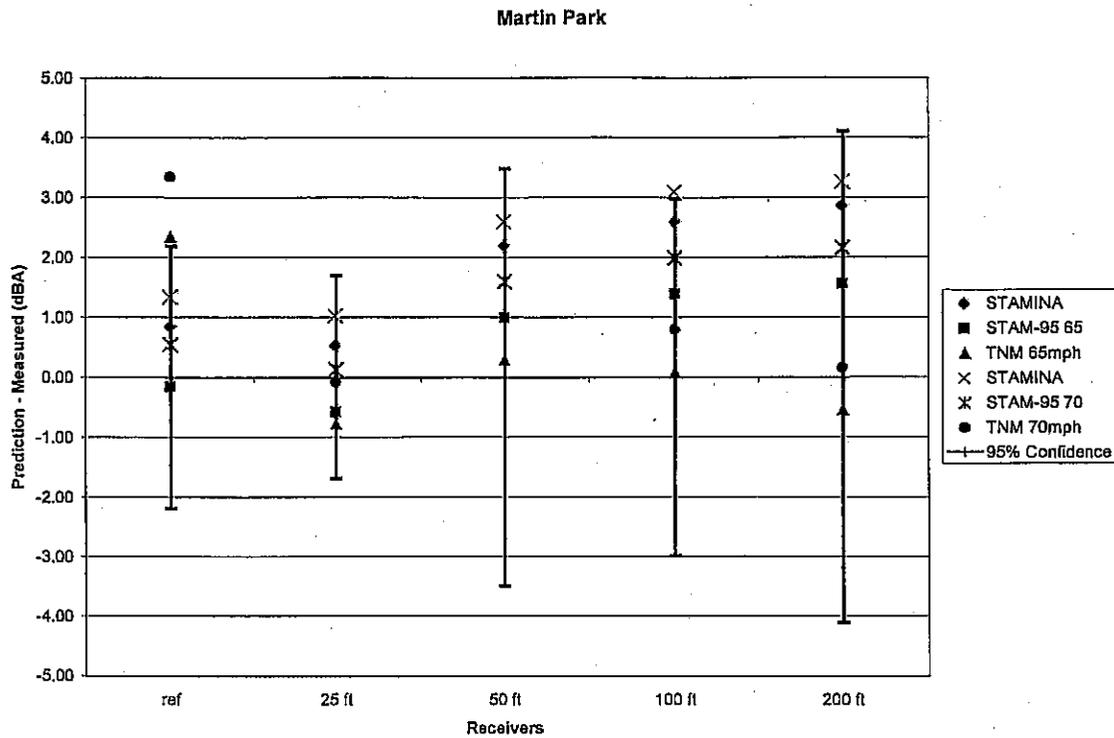


Figure 3-27 Differences between Predicted and measured noise - Martin Park.

Hinsdale - I-294 North of 55th Street (8-19-1998)

The Hinsdale TNM analysis included terrain lines to represent the berms behind the barrier as shown in Figure 3-28. The comparison of the predicted and measured noise levels are shown in Figures 3-29 and 3-30. The bar chart for this site is organized identically to Farmwood and Martin Parks, with three prediction analyses at speeds of 65 mph and 70 mph, along with the measured traffic noise. At the reference location, two of the predictions are outside the confidence limits -- TNM at 70 mph over-predicted and the updated STAMINA under-predicted noise levels. At the 25 ft receiver location, only the original STAMINA predictions are outside the confidence limits. At the remaining receiver locations, only the TNM predictions are within the confidence limits. At this site, STAMINA tended to over-predict the measured noise levels. The updated STAMINA reduced the over-prediction.

3.3.4 Discussion of Field Measurement and Analysis

At the reference microphone locations, which were above the noise barrier, TNM provided a significantly better prediction of the measured traffic noise levels. STAMINA tended to under-predict the noise levels at the reference locations. The under-prediction ranged from 0.5 dBA to 4 dBA. Updating the noise coefficients in STAMINA had only a minor effect, although it further decreased the predicted noise levels. Since the reference location microphone was positioned well above the barrier wall, the noise predictions are not influenced by the existence of the barrier. So, the diffraction models in the analysis programs are not responsible for the differences in predictions. The improved predictions with the TNM model may have been due to its use of ground reflected noise in addition to

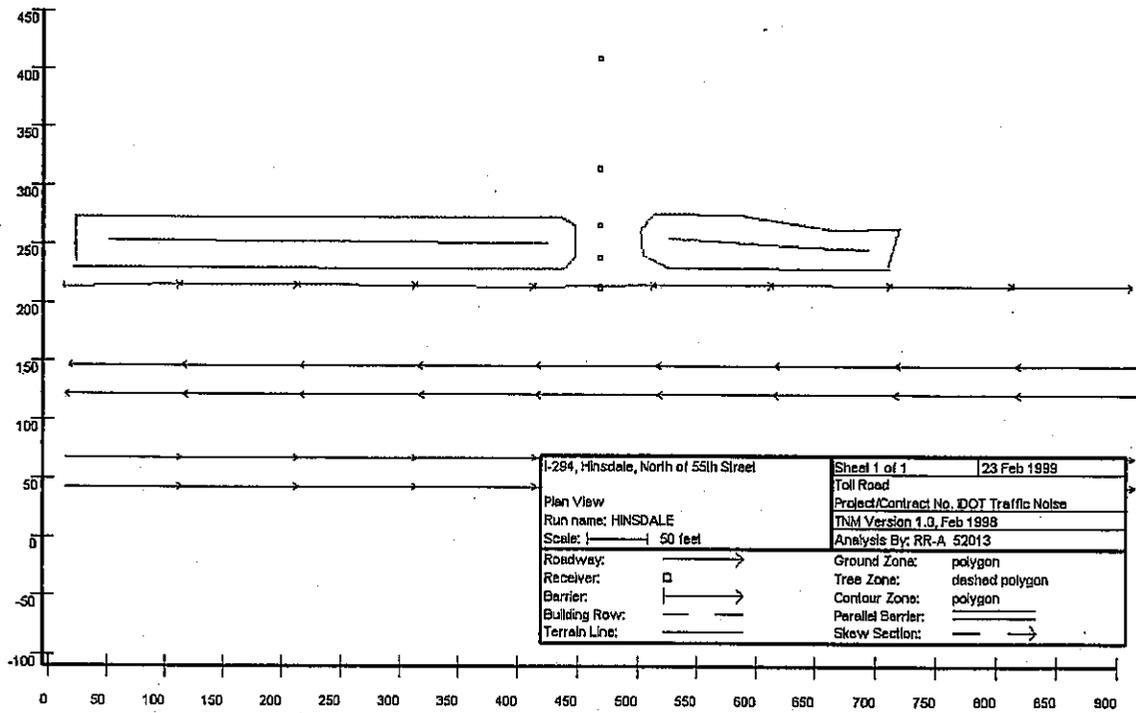


Figure 3-28 Hinsdale analysis.

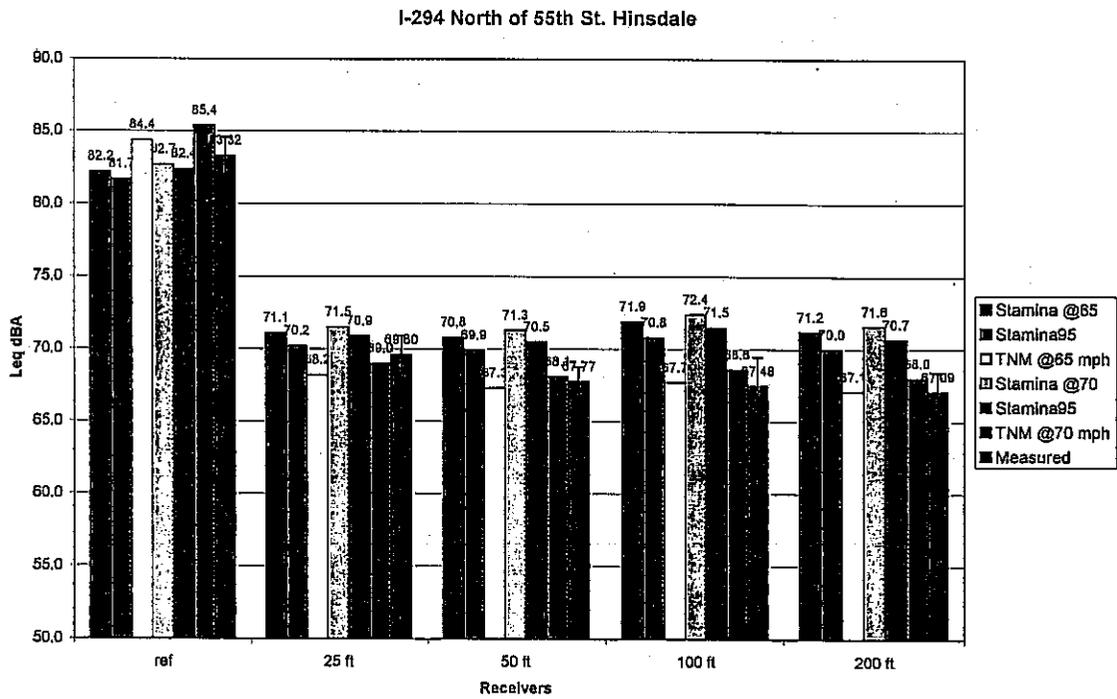


Figure 3-29 Comparison of predicted and measured noise levels - Hinsdale.

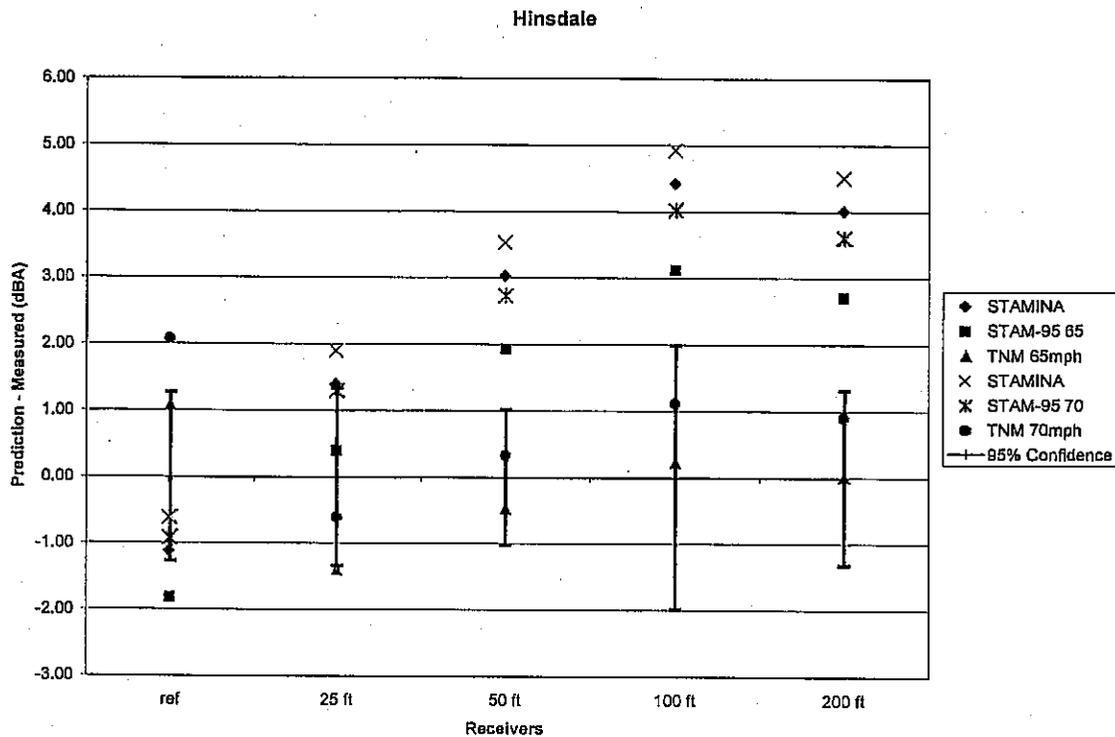


Figure 3-30 Differences between predicted and measured noise - Hinsdale.

the direct noise path that was used in STAMINA. The multiple noise paths account for the higher predicted noise levels.

At the receiver locations, 5 ft above the ground, the comparison is not as clear. At two of the sites, Farmwood Park and Hinsdale, the original STAMINA program showed a significant over-prediction relative to TNM and the actual measured noise levels. The STAMINA predicted noise levels were 2 to 5 dBA greater than the measured noise levels and they were outside the 95% confidence limit in all but one location. The updated REMELs in STAMINA reduced the over-prediction by 0.5 to 1 dBA for both sites. At the two other sites, Maple Street and Martin Park, the STAMINA analysis predictions were all within the 95% confidence limits, so it adequately predicted the measured noise levels. The updated REMEL in STAMINA reduced the predicted noise levels by about 1 dBA at the Martin Park site but by less than 0.5 dBA at the Maple Street site.

3.3.5 Measurement Conclusions

In general, the TNM predictions agree well with the measured traffic noise levels as they are essentially within the 95% confidence limits. The updated REMEL in STAMINA improved the over-prediction, with the predictions for three of the four sites are generally within the 95% confidence bounds. However, the updated REMEL did not significantly improve the under-prediction of the STAMINA program at the reference locations above the noise barrier.

The results for these four sites raise questions about the accuracy of the prediction programs for locations significantly above the ground. The study team suggests that a future study include observer locations significantly above the ground. Another concern is the accuracy of TNM at greater distances from the highway. The current study considered locations only up to 200 ft. A future study should consider distances of 500 ft or greater to assess the greatest distance from the barrier that should be used in TNM.

3.4 Influence of FHWA TNM 1.0 Features

Since the FHWA TNM 1.0 traffic noise prediction program became available only recently, the sensitivity of some of its features were examined. Various TNM features were removed one at a time from the analyses already presented to indicate their effect on the noise predictions. Although not an exhaustive evaluation of the TNM features, this highlights the influences of these features.

3.4.1 Ground Zones

The Maple Street and Martin Park sites included paved areas behind the barrier that were modeled in TNM using ground zones. The Maple Street analysis included two ground zones to represent the surface street parallel to the barrier and Maple Street along which the noise measurements were taken. Contour plots showed unexpected irregularities parallel to the barrier. However, this irregularity was only noted with the barrier; without the barrier the contour lines were nearly parallel to the barrier as expected.

To investigate this irregularity in the Maple Street analysis, a series of receivers were added in three lines, perpendicular to the barrier separated by 50 ft and at 50 ft intervals behind the wall. Adjacent receivers, parallel to the barrier, showed differences of as much as 3.4 dBA, which was greater than moving perpendicular to the barrier. Initially, it was guessed that the ground strip perpendicular to the barrier might be responsible for the higher noise levels. However, the receivers in this hard surface ground strip were not always higher than those in the surrounding grassland. Elements were removed one at a time to see which was responsible for the lateral variations. When only the ground zone parallel to the barrier was used, the lateral difference was 3.5 dBA at 50 ft from the barrier. The contours with only the parallel ground zone are very similar to the full analysis up to 150 ft behind the barrier. The differences further from the barrier may be due to the house row at 75 ft behind the barrier. On the other hand, when only the ground zone for Maple Street was used, the maximum lateral difference was reduced to 1.8 dBA at 50 ft from the barrier.

The large variation in noise levels for observers parallel to the barrier seems to be related to the ground zone just behind the barrier. The TNM technical manual notes that ground zones introduce impedance discontinuities that cause diffraction-like changes in magnitude and phase. This has the potential to cause interference. However, it is not clear that the predicted interference is realistic. This behavior warrants further investigation and field measurements to clarify.

The Martin Park site also used ground zones. At this site, the line of observers crossed a paved parking area and there was a small pond about 300 ft south of the observers. The pond

ground zone had zero impact on the noise predictions. The ground zone used to represent the parking area had a very small effect, between zero and 0.3 dBA. Therefore, unlike Maple Street site, these ground zones had an insignificant effect on the noise predictions.



Figure 3-31 Skew view of Farmwood Park site

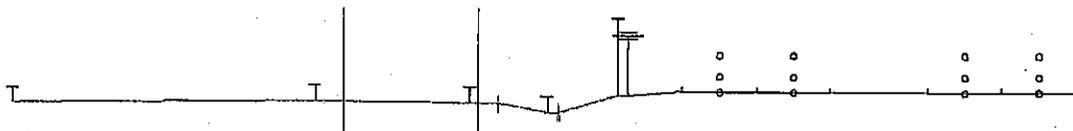


Figure 3-32 Skew view of Martin Park site.

3.4.2 Terrain Lines

Three of the measured sites included terrain lines in their TNM analyses - Farmwood Park, Martin Park, and Hinsdale. The analyses for Farmwood Park and Martin Park used terrain lines to represent features along a significant length of the barrier. In the Farmwood Park site terrain lines were used to model the berm and edge of a dry, retention pond (Figure 3-31). The Martin Park site had a drainage ditch behind the barrier that was represented by terrain lines (Figure 3-32). There was only a small change at the line of observers; the maximum change was 1.3 dBA but most were less than 0.5 dBA. The Hinsdale site used terrain lines to represent the berms on either side of the line of observers. In this analysis removing the berm terrain lines had zero effect on all the noise predictions.

The analysis of I-78 in Pennsylvania (one of the test problems for the updated REMELs in STAMINA) had a complex site geometry. On the far right of the site, there was a river in a ravine with the observers on a ridge (Figure 3-33). The results presented in Section 3.2 did not include the terrain lines or the ground zone representing the river. This was due to the difficulty of successfully running this analysis (see Section 3.1.3). Many weeks were spent "tinkering" so that the analysis would run to completion. After this extended effort, the terrain lines and ground zone had a relatively small effect on the predicted noise levels. The river and the terrain lines caused a maximum change of 1.0 dBA at receiver 27 while the majority of the changes were less than 0.5 dBA. When the terrain lines only are removed (retaining the ground zone representing the river) the maximum difference was 1.4 dBA at receiver 27 compared to the analysis without any terrain lines and ground zones. Again, the majority of differences were less than 0.5 dBA. This site had fairly extreme terrain geometry, yet including these features in TNM had relatively small effect on the predicted noise levels.

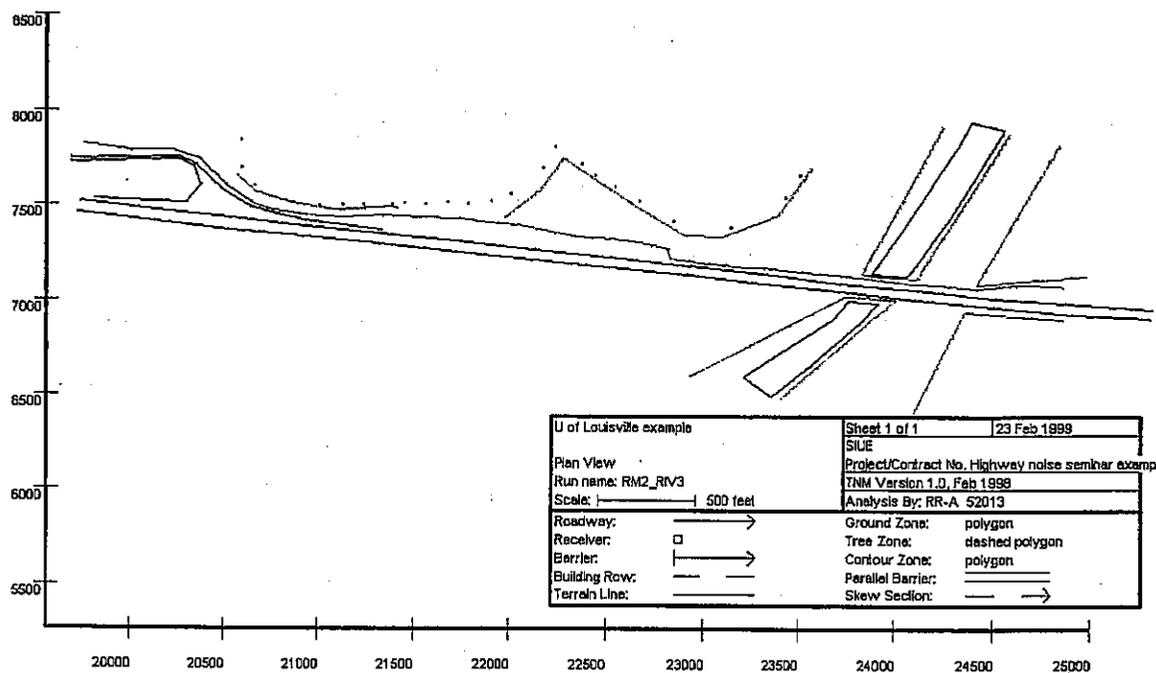


Figure 3-33 I-78 in Pennsylvania with terrain lines and ground zones for river.

3.4.3 Entrance Ramp Modeling

Three of the four test problems in Section 3.2 had entrance ramps that were modeled in TNM. The TNM verification problem, I-78 in Pennsylvania and I-355 in Addison, IL analyses each had one entrance ramp with a small quantity of traffic. The TNM entrance ramp modeling feature assumes that the vehicles are accelerating. The entrance modeling had only a minor influence on the predicted noise levels. The maximum change due to the ramp was 0.6 dBA. In addition, the differences were slightly higher with the barrier instead of without the barrier. The change is localized in the vicinity of the ramps.

3.4.4 Shadow Zone - Spatial Comparison Between TNM and STAMINA

The spatial noise propagation differences between TNM and STAMINA analyses were compared using shadow zone contour plots similar to those depicted in Section 2.3.2. The analyses to produce the shadow zone plots were based on a simplified version of the Farmwood Park site, where the barrier height was 12 ft and a level terrain behind the barrier at the elevation of the original 50 ft receiver. These shadow zone contour plots are shown in Figures 3-34 to 3-37 for STAMINA with $\alpha=0.5$ (soft ground) and $\alpha=0.0$ (hard ground), and TNM with default ground types of lawn and pavement respectively. The STAMINA shadow zone contour plots have a similar appearance to those from Hajek et al. [1983] (Figure 2-2) using STAMINA 1.0. The only difference is that the current soft ground contours do not show discontinuities. The STAMINA IL contours suggest that at 5 ft height an 8 dBA IL limit occurs around 75 ft behind the barrier. The hard ground case shows significant differences both beyond 200 ft and above the barrier height.

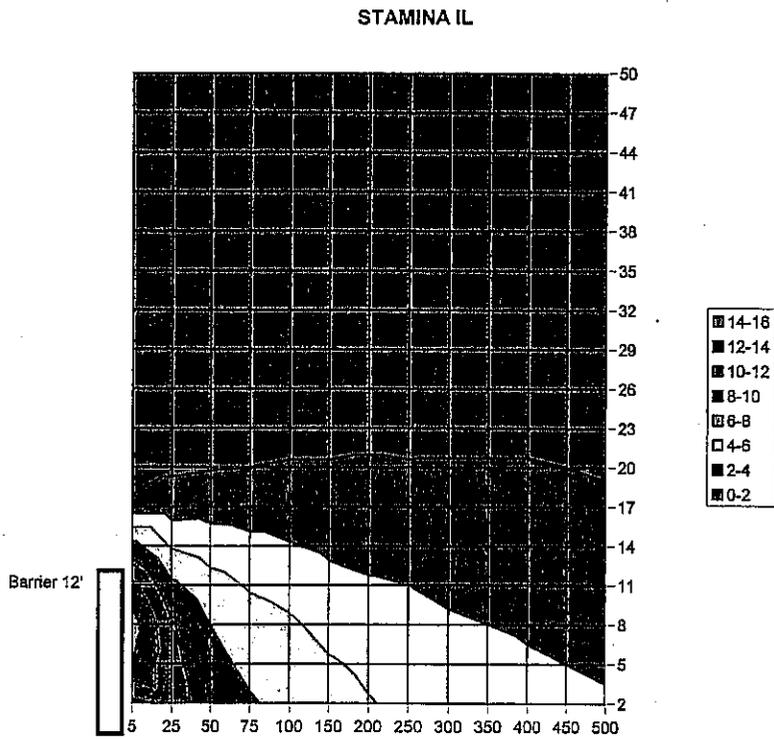


Figure 3-34 Shadow zone - STAMINA 2.0 with $\alpha = 0.5$ - soft ground.

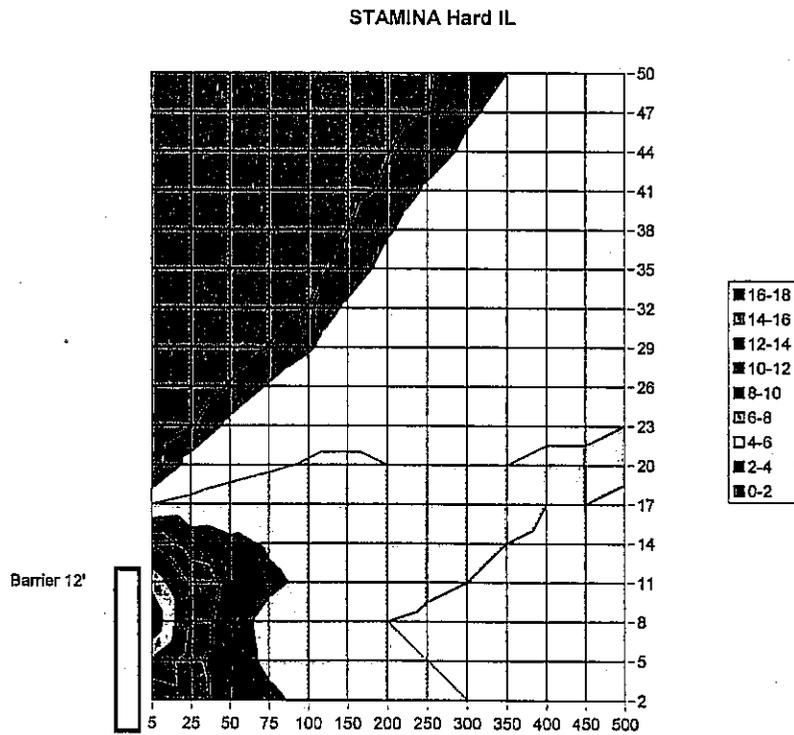


Figure 3-35 Shadow zone - STAMINA 2.0 with $\alpha = 0.0$ - hard ground.

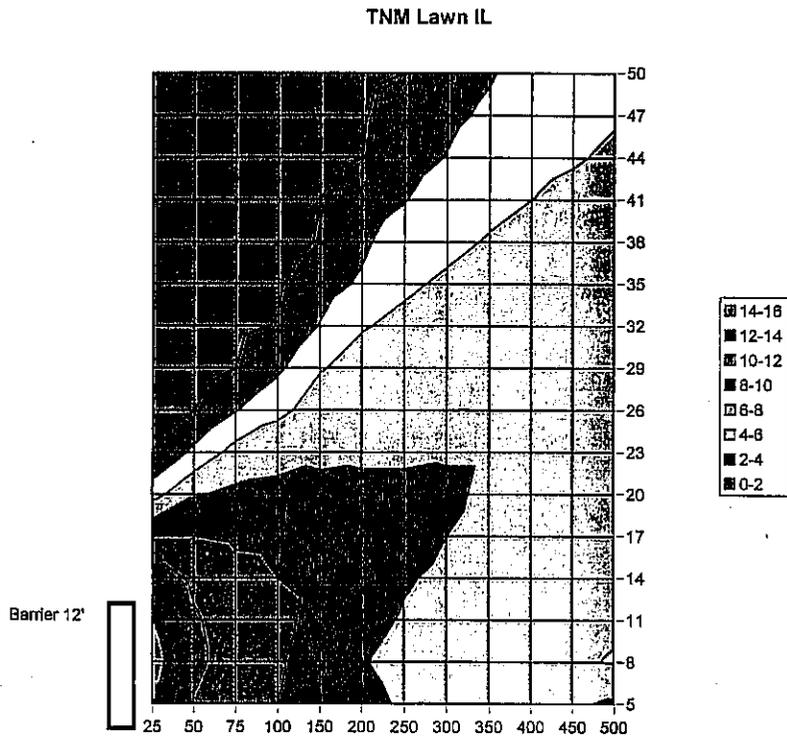


Figure 3-36 Shadow zone - TNM 1.0 - Lawn.

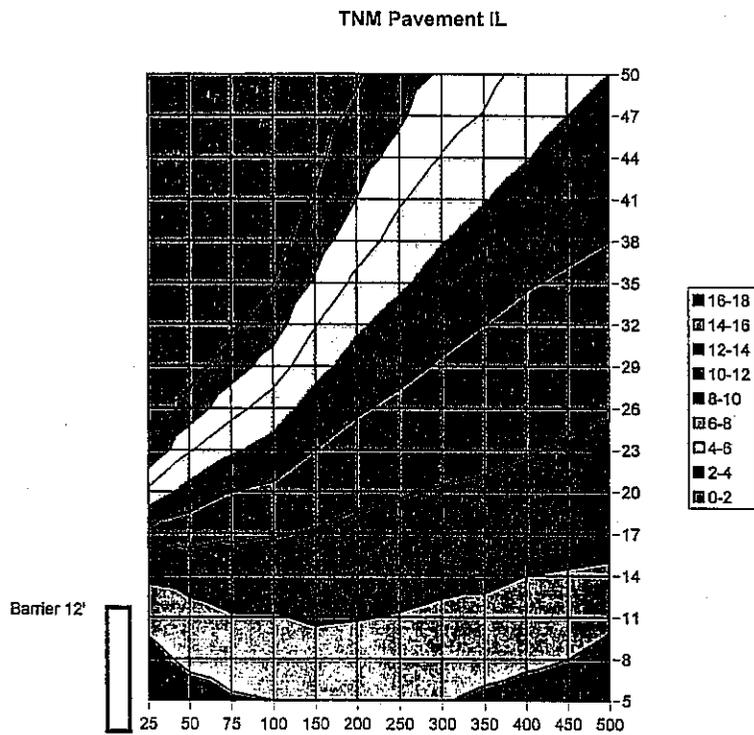


Figure 3-37 Shadow zone - TNM 1.0 - Pavement.

The TNM shadow zone contours show significantly larger IL values than those predicted by STAMINA. Even though TNM predicted lower noise levels at 5 ft height, the IL is still typically larger than predicted by STAMINA. The TNM shadow zone for lawn appears similar to the contours from Fujiwara et al. [1998] (see Figure 2-4). Note that, for both the hard and soft ground, the 8 dBA line extends from above the barrier upwards. However, the soft ground 8 dBA contour bends back down towards the ground 300 ft. The 8 dBA IL for TNM is about 250 ft behind the barrier at 5 ft height and soft ground. With hard ground the 8 dBA IL is beyond 500 ft.

Chapter 4 Top Treatments

The concept of top treatments is to modify the top edge or surface of the noise barrier in an effort to increase its effectiveness without significantly increasing its height or cost. The height of the barrier is related both to its cost, as well as additional design requirements for its footings. As a whole, top treatments have been infrequently used in the U.S., but have been widely used in Japan [Bowlby and Cohn, 1986].

The literature on top treatments has been reviewed and is summarized below by type of top treatment. Then the FHWA traffic noise prediction programs STAMINA and TNM are examined to assess if they can reasonably predict the effectiveness of top treatments for use in Illinois.

4.1 Types of Top Treatments

The world's traffic noise researchers have shown significant creativity in proposing numerous types of top treatments. The types of top treatments considered include wide barriers, multiple barriers, T- or Y-top barriers, cylindrical top barriers, and special treatments (Figure 4-1). These top treatment candidates have been evaluated through analytical models, scale models, full-scale model, and actual roadside tests.

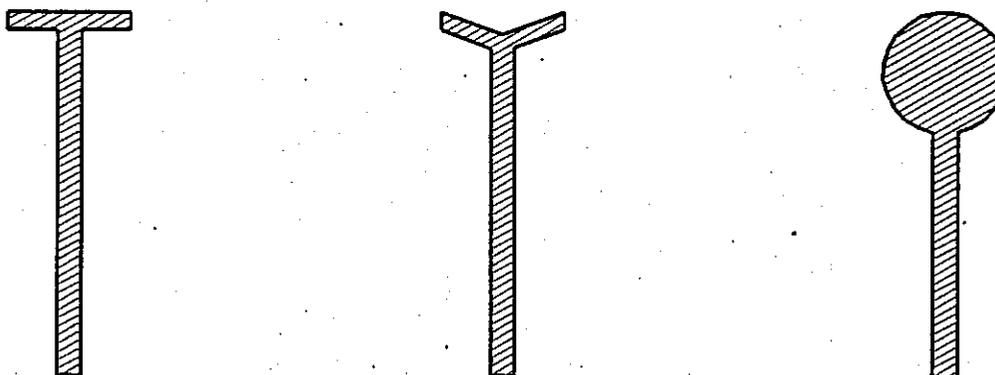


Figure 4-1 Top treatments, T-top, Y-top, and Round-top.

4.1.1 Wide - Double Edge Barriers

The simplest modification to the basic noise barrier is to increase its width so that there are two edges to cause diffraction. This wide barrier concept was considered by Fujiwara et al. [1998], using a 2-D BEM analysis. They noted only a very marginal improvement of 0.7 dBA for a barrier height of 3 m and width of 1 m. The wide barrier is not efficient since a significant amount of material would need to be added to the barrier, increasing the cost.

4.1.2 T and Y Top Barriers

Instead of increasing the whole width of the barrier, T- and Y-top barriers only increase the width of the top edge to provide multiple diffracting edges. A number of studies have been conducted to evaluate the effectiveness of these shapes [Fujiwara et al., 1998; Cohn et al.,

1993; Watts et al., 1994, and Shima et al., 1996]. Cohn et al. suggests that the T-top can increase insertion loss by about 2 dB for a top width of 0.41 m (16 in.), while Fujiwara et al. predict an improvement of 1.3 dB for a 1 m wide top using BEM analysis. Both indicate additional improvement when top surface is absorptive. Cohn suggests that the absorptive material provides an additional 1.9 dB insertion loss, while Fujiwara reports an additional 3.8 dB improvement. Watts et al. indicate that the T-top barrier is most effective at frequencies above 400 Hz and provides no improvement at lower frequencies. This reduction in performance is related to the noise wavelength. The 400 Hz wavelength, λ , is about 1 m, which is approximately the width of the T-top. At lower frequencies, the T-top width is smaller than the wavelength and noise will not be diffracted by both edges.

In general, the Y-top has just slightly poorer performance than the T-top. Cohn et al. indicates concern with water being trapped atop the barrier by the Y shape. Shima et al. [1996] claims significant improvement of the basic Y-top by adding additional diffraction edges. Their prediction was done with a BEM analysis and has not yet been evaluated in full-scale tests.

4.1.3 Round or Elliptical Top Barriers

Round and elliptical barrier tops are alternative top treatments. Fujiwara et al. [1998] suggested that a 1 m diameter round top actually reduced the insertion loss, a negative improvement, as compared to a reference barrier of the same height. On the other hand, if the round top is absorptive the insertion loss is increased by 3.9 dB. A full-scale test of an elliptical top was conducted for Cal-DOT in Los Angeles county [Persons Engineering, 1994 and Gharabegian, 1996]. The test results for the Noise Reducer showed only marginal improvement of less than 1 dB. The top treatment increased the height of the barrier by 0.46 m and it provided the noise reduction equivalent to increasing the barrier height by 0.6 to 1.1 m without a top treatment. The study also suggested that the elliptical top was more effective at lower frequencies than high frequencies.

4.1.4 Multiple Barriers

The T- and Y-Top modifications were effective because of their multiple edges for diffraction. If two edges are good, maybe more are even better. This prompted investigations to consider more than one barrier between source and the receiver.

Crombie and Hothersall [1994] studied a wide range of multiple barriers using BEM and scale-model testing. They concluded that multiple barriers were most effective for barriers of similar height placed as far apart as possible. They predicted that two 3 m barriers placed up to 12 m apart provided an improvement of 9.8 dB in noise reduction. The total insertion loss was approximately 24 dB, which is near the maximum of 25 dB for outdoors sound propagation. In a separate study, Watts et al. [1994] tested multiple full-scale barriers using a loud-speaker noise source. In this study barriers that were 2 m high and separated by 4 m and 8 m provided insertion loss improvements of 3.1 and 3.7 dB respectively, which was similar to BEM predictions. These experimental results also indicate that the region of added noise reduction was below the barrier height. An observer significantly above the barrier, but still in the shadow zone, will not receive the benefit of the second barrier.

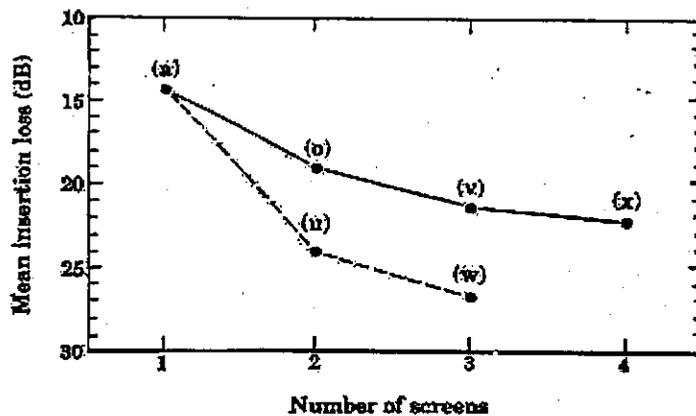


Figure 4-2 Crombie and Hothersall [1994] noise levels from multiple barriers. Solid = shorter barrier in front, dashed = same height barrier.

Crombie and Hothersall also considered the influence of adding more than two barriers between source and observer. They reported insertion loss improvement when additional barriers are added, provided that the intermediate barrier is higher than the one nearer to the noise source (Figure 4-2). When additional barriers are added, the additional improvement diminishes for more than three barriers in a row.

Crombie and Hothersall also evaluated adding absorption to the face of the multiple barriers and concluded that it did not significantly improve barrier performance. It did, however, reduce the peaks and valleys in the spectrum due to regions of constructive and destructive interference.

The concept of multiple diffracting edges was extended to consider attaching multiple edges to the original barrier. Crombie et al. [1995] studied multiple-edge barriers using BEM and scale-model testing, and Watts et al. [1994] conducted full-scale testing with a loud-speaker noise source. Crombie et al. reported that improvements in insertion loss from 2 to almost 5 dB could be achieved by adding from one to four additional panels offset from the original

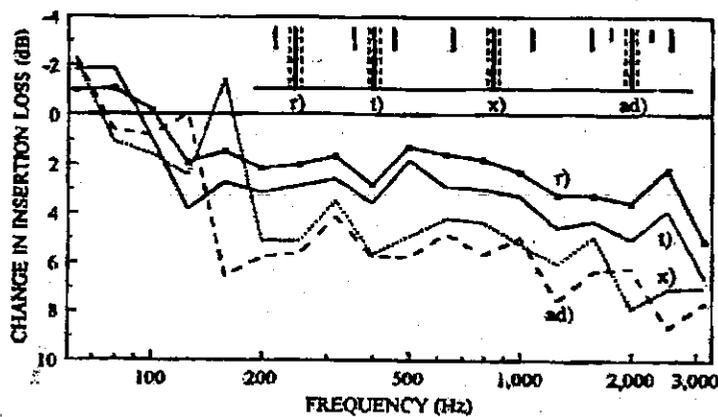


Figure 4-3 Crombie et al. insertion loss improvement by adding additional panels. Dashed lines on barrier are absorptive face.

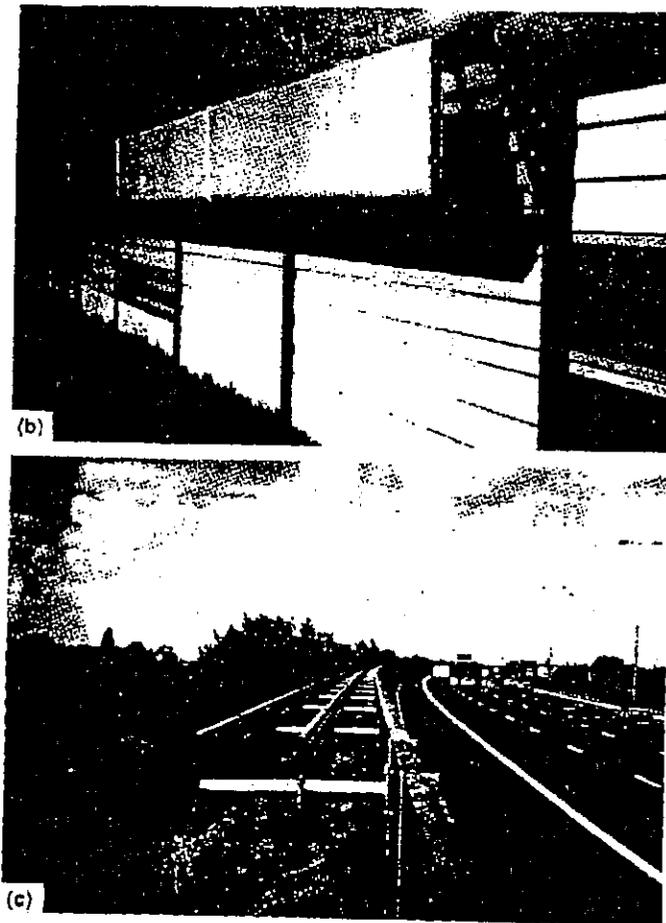


Figure 4-4 Top treatments used in Watts [1996], and Watts and Morgan [1996].

noise barrier (Figure 4-3). The added edge panels were slightly more effective on the source side than the receiver side of the barrier. If the space between the added panel and the barrier has a closed bottom, the insertion loss improvement was greatly diminished. Full-scale test of multiple edge barriers was conducted along the M25 London orbital motorway using actual traffic as the noise source [Watts, 1996; and Watts and Morgan, 1996]. The barrier top treatments used in these two studies are shown in Figure 4-4, where the first was a multiple edge treatment and other was a open-top box behind the barrier to provide wave interference for enhanced performance. The multiple-edge barrier showed an average improvement of up to 3 dB and the interference treatment had an improvement of about 2 dB. The interference device seemed to derive about two-thirds of its improvement from multiple edge diffraction rather than wave interference (the entrances to the interference slots were blocked with sections of 12 mm plywood). The lower performance for the interference device was attributed to the closed bottom between the main barrier and the back panel. Despite its poorer reported performance, the interference device is in use along railways in Austria, Germany, Italy, and Japan.

These full-scale tests using actual traffic as the noise source showed slightly poorer than expected based on BEM and scale-model testing. This raised concern that there may be

significant noise transmitted through the barrier [Watts, 1997]. Normally, the noise transmission through barriers is considered to be insignificant when the transmission loss is on the order of 25 dB or more. The barrier in question was wooden and the transmission loss was measured *in situ* employing traffic noise as the noise source. Watts found that these wooden barrier panels had about 15 dB lower transmission loss than expected based on surface density, which ranged between 5 to 18 dB over a frequency range of 200 to 41K Hz. Watts suggested that the poorer performance might be due to noise leakage through cover strips covering the gaps between the boards. This study has raised many questions regarding the performance of many older barriers that have developed small gaps through the years. This indicates the need to adequately seal barrier panels to support columns.

4.1.5 Random Edge Barriers

Researchers at the University of Texas at Austin have been investigating the use of random edge barriers to improve insertion loss [Rosenberg and Busch-Vishniac, 1997; Ho et al., 1997; and Klingner et al., 1996]. The concept is that a straight edge barrier appears to have a series of imaginary point sources along its top edge due to the diffraction of the traffic noise. If these imaginary sources are coherent due to their spacing along the wall, they interfere to create higher and lower noise zones behind the wall. This interference leads to variations in insertion loss in the shadow zone "near" the barrier. This coherence of the edge sources might be disrupted by introducing some randomness to the top edge of the barrier. This concept was tested using scale model barriers with a spark point source. The spark point source guaranteed the coherence of the edge sources and allowed a fairly short test barrier to appear infinitely long to avoid edge effects at the ends of the wall. The scale model tests show insertion loss improvements of 2 to 5 dB with the random edge. The improvement was not uniform for all frequencies and there was negative improvement for low frequencies. Because the random edge was tested as a scale model, there will be scaling effect on the test frequencies that the authors did not discuss. Because the spark source was not a realistic representation of traffic noise and there is not a clear scale factor for the model, it is not possible to relate the frequencies where this negative insertion loss would start for actual barriers. The scaling effect is such that, if the barrier dimensions are affected by a scale factor S, time would be scaled by \sqrt{S} and frequencies would be scaled by $1/\sqrt{S}$.

The concept of a random edge barrier is somewhat controversial in that traffic noise researchers are not in agreement about the possible coherence of the diffraction sources. It is common to consider traffic noise as emanating from a line source for moderate to heavy traffic volumes (>1000 vph). This stationary line source is actually a series of moving individual sources that are not in sync with each other and are at random spacing. It is more appropriate to consider traffic noise as incoherent. In addition, the random edge effect is most effective for high frequencies that naturally dissipate quickly, and has little or negative effect on low frequency noise, which is a significant cause of traffic noise annoyance.

4.2 Absorptive and Soft Faces on Barriers

As mentioned previously, many researchers have considered adding absorption to the barrier face or top to improve noise reduction. There are mixed conclusions regarding the additional effectiveness of absorptive surfaces. Fujiwara et al. [1998] reported that making the top

absorptive for wide, round top, or T-top barrier increases the insertion loss by approximately 4 dB. On the other hand, full-scale field test in Toronto reported a moderate improvement of 1 to 1.5 dB when absorption was added to a T-top barrier [Cohn, 1993]. Crombie and Hotersall [1994] also reported a moderate improvement of about 1 dB based on a BEM analysis for multiple barriers with absorptive surfaces.

When considering use of absorptive surfaces, it is necessary to consider the durability of the absorptive material. One of the common absorptive surfaces used in the U.S. is porous concrete, which when subjected to freezing and thawing was easily damaged, especially for top surfaces with poor to moderate drainage. A study was conducted by FHWA and Maryland-DOT [Cohn 1993] on freeze-thaw damage of porous and standard concrete. In 200 cycles, the porous concrete lost 60% of its surface while the standard concrete showed no deterioration.

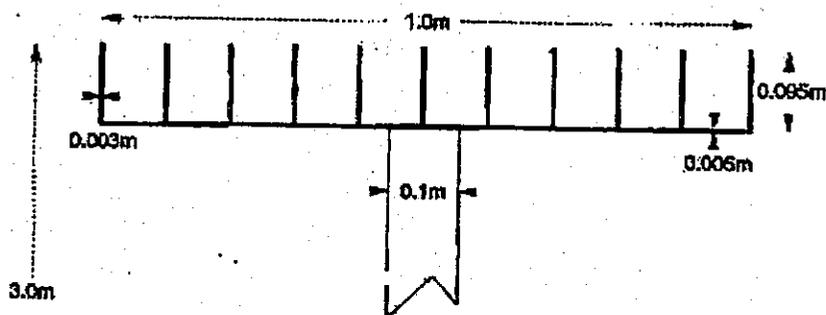


Figure 4-5 Soft T-top barrier, Fujiwara et al. [1998].

Recently some researchers have proposed using "soft" surfaces instead of absorptive surfaces to enhance the performance of noise barriers. A soft surface is a bit different than an absorptive surface. Technically, a rigid or hard surface has a zero surface admittance, an absorbing surface has a surface impedance of about 1, and a "soft" surface has a surface impedance of zero or significantly less than that of air. For a soft surface, the surface pressure approaches ambient conditions and virtually all the noise pressure is eliminated after contact with the surface. This has the effect of virtually eliminating the imaginary diffraction source - normal hard edge barriers. However, it is difficult to identify materials with very low impedance. Instead, some researchers have proposed using a series of wells or 1/4-wave tubes to generate destructive interference to emulate a soft surface. Unfortunately, these tubes cannot be "tuned" to all frequencies. The soft T-top analyzed by Fujiwara et al. [1998] appears to have a series of fins and has a projected increase of insertion loss on the order of 7 dB over a rigid T-top (see Figure 4-5). A soft cylinder, with the appearance of a water wheel (Figure 4-6), was tested as a scale model by Okubo and Fujiwara [1998]. The soft cylinder may provide as much as 12 dB increase in insertion loss. So far the study of soft surfaces is still at the stage of theoretical analyses or scale model testing. There have not been any field test reported.

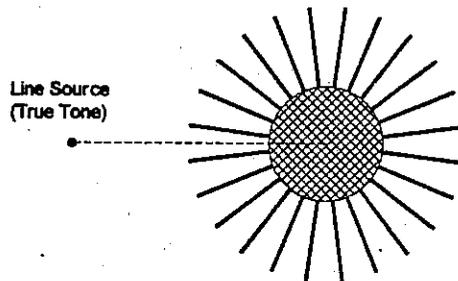


Figure 4-6 Soft round-top, water-wheel, Okubo and Fujiwara [1998].

4.3 Active Noise Control to Improve Barrier Performance

Recently researchers have begun to consider active noise control to improve the performance of noise barriers. The concept of active noise control is to use secondary noise sources that interact with the primary noise source to create destructive interference or quiet zones. To accomplish this destructive interference requires a controller that monitors the noise source and then generates appropriate secondary sources to achieve cancellation. Researchers in Japan have proposed combining active noise control with noise barriers to create a quiet zone near the diffraction edge of the barrier [Shao et al., 1997, and Guo and Pan, 1997]. In principal, this is similar to barriers with soft surfaces, but the interference is achieved by introducing an additional noise source. So far, theoretical predictions and scale model studies show that the low frequency performance of the barrier can be significantly improved, which is difficult to achieve by the passive top treatments and soft surfaces. The attenuation increases when the secondary sources are nearer the primary source. Also, the attenuation increases with more secondary sources.

4.4 Analysis to Predict Top Treatment Effectiveness

Researchers claim a wide range of effectiveness for top treatments. Top treatment effectiveness should be a function of type of treatment, site configuration, and traffic conditions. Therefore, it is desirable to have a means to evaluate the effectiveness of top treatments for sites in Illinois. We assessed the use of the existing FHWA traffic noise prediction programs to evaluate the effectiveness of top treatments.

The STAMINA program has no potential to evaluate the effectiveness of top treatments. STAMINA uses Fresnel diffraction to predict the change in noise intensity due to a barrier. The only parameters considered are the height of the barrier and its location relative to the noise source and receiver. The profile shape of the barrier, its thickness, and top shape are not considered.

The FHWA TNM program holds some potential to predict the effectiveness of top treatment, but not directly. The base TNM algorithm is similar to the Fresnel diffraction used in STAMINA, where diffraction is based on the barrier's height and placement. The thickness

and plan shape of the barrier are not considered in the main algorithm, however, the barrier's profile shape is considered in the parallel barrier module.

The TNM parallel barrier module was evaluated to predict the effectiveness of top treatments in Illinois. The parallel barrier analysis, based on multiple reflections, starts from an existing TNM analysis. The parallel barrier analysis is displayed as an elevation view that is cut from the standard analyses' plan view. The section will automatically contain any roadway, barrier and receiver in the cut line. Additional traffic sources and receivers can be added as appropriate. The barrier profile is defined in the parallel barrier cross section menu option as a single surface. The cross section can have absorptive surfaces that are indicated by noise reduction coefficients (NRC). After the configuration is modeled, the increase in noise due to multiple reflections is predicted by selecting the calculate menu option.

The parallel barrier top treatment assessment was done with two of the sites from the field measurements (see Section 3.3). The two test sites were the IDOT sites of Farmwood Park and Maple Street. The Maple Street site was the only one of the four field measurement sites that actually had parallel barriers, in addition, the roadway was depressed (cut section) so that it passed under Chicago Ave. The parallel barrier analysis at the measured receiver locations predicted zero increase in noise level. So, a location north of the actual measurement site was used instead where the roadway was on grade with the receivers behind the barrier (with receivers at distances of 25', 50', 100', and 200' behind the barrier). The noise level increase was still relatively small at less than 1 dBA. In order to predict a higher noise level increase, the roadways were moved closer to the barriers, which resulted in parallel barrier noise increase from 4.1 to 6 dBA. This modified highway configuration was used to evaluate a T-top configuration, where the predicted parallel barrier noise increases are summered in Figures 4-7 and 4-8 for a 3 m (9.6 ft) tall barrier with varying T-top width. Figure 4-7 is for a reflective barrier and Figure 4-8 is for an absorptive barrier with NRC of 0.5. Both charts show an initial decrease in noise level, as the width of the T-top is increases. Then the noise levels increase for T-top width over 1 m. This predicted behavior is not reasonable. It is expected that increasing the width of a T-top should continue to decrease the noise reduction or reach a limit, but not to increase the noise level.

The second test case was Farmwood Park. The Farmwood Park site did not have parallel barriers and predicts zero increase in noise level without the parallel barriers. Thus, a parallel barrier was added as a mirror image of the original barrier, which gives a noise level increase of 1.0 to 1.6 dBA. A possible reason for the relatively low noise increase might be the generous 75 ft berms. To increase the noise level the berms were reduced to 24 ft on each side, so that the parallel barrier canyon width to height ratio was 10.7 for a 12 ft (3.75 m) barrier height. The predicted parallel barrier noise level increase was 3 to 5.3 dBA, which is about 1 dBA less than for the Maple street site. Similar to the Maple Street site, results of analyses for T-top treatments are shown in Figures 4-9 and 4-10 for reflective surfaces and absorptive with a NRC of 0.5 respectively. The Farmwood Park analyses show a similar trend as Maple Street, but with slightly less change. The Farmwood Park has the same questionable behavior, where the wider T-tops show reduced effectiveness.

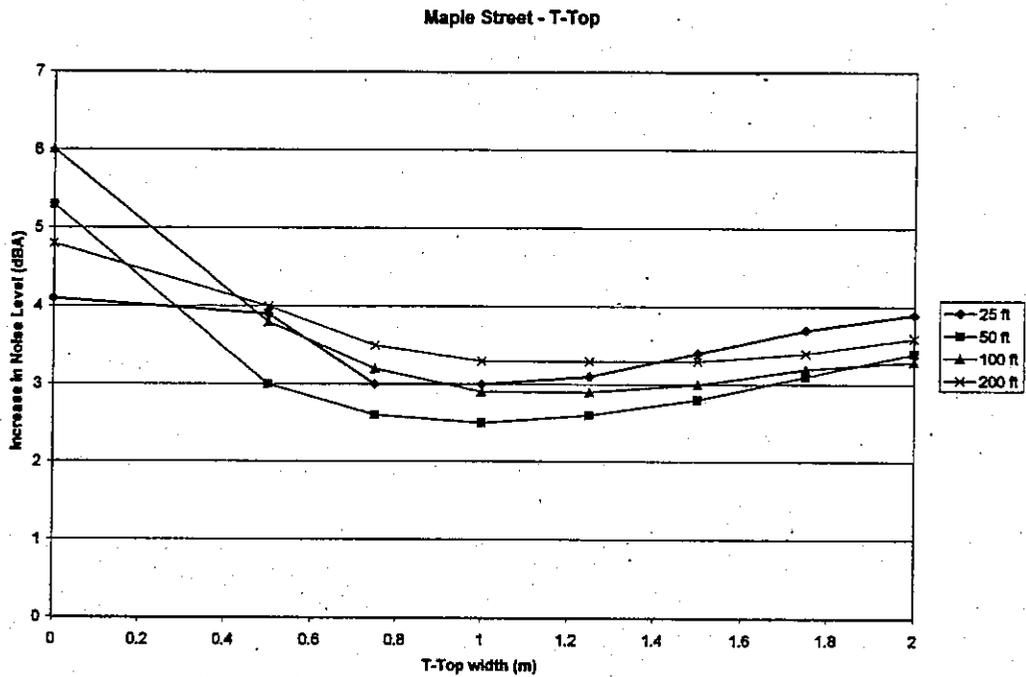


Figure 4-7 TNM parallel barrier analysis for a T-top treatment - Maple Street - Reflective - NRC = 0.0.

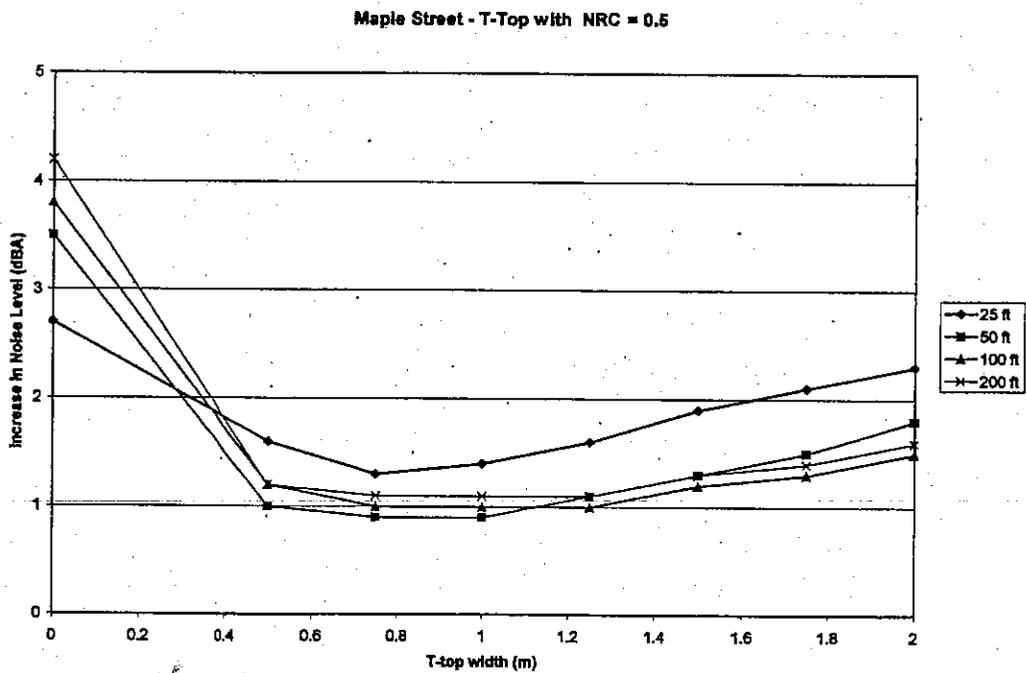


Figure 4-7 TNM parallel barrier analysis for a T-top treatment - Maple Street - Absorptive - NRC = 0.5.

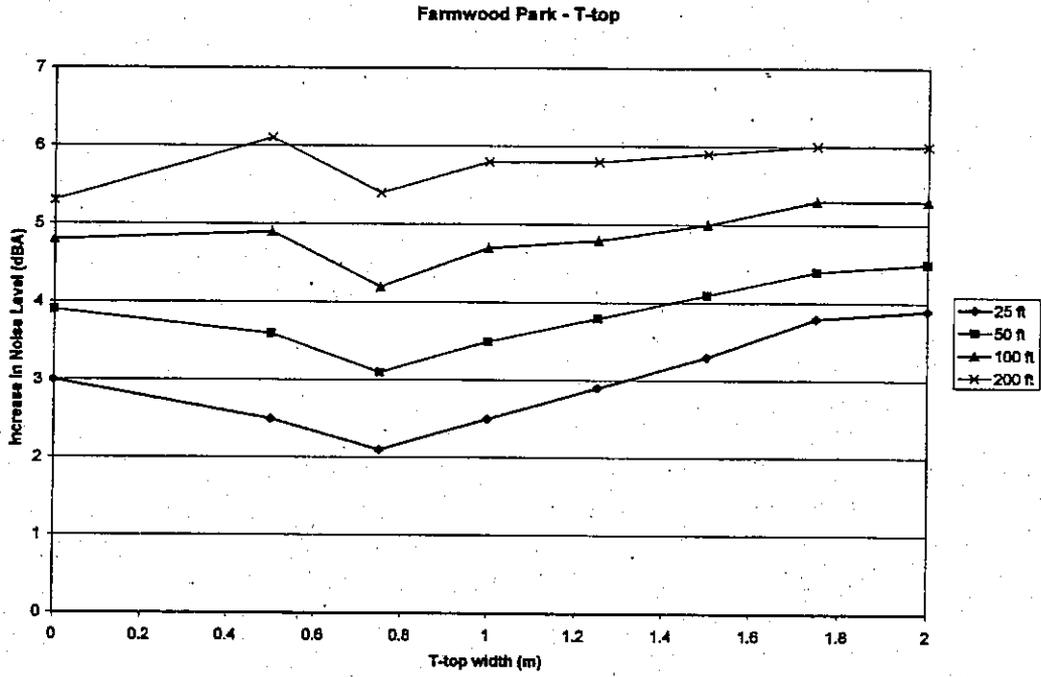


Figure 4-9 TNM parallel barrier analysis for a T-top treatment - Farmwood Park Reflective - NRC = 0.0 ..

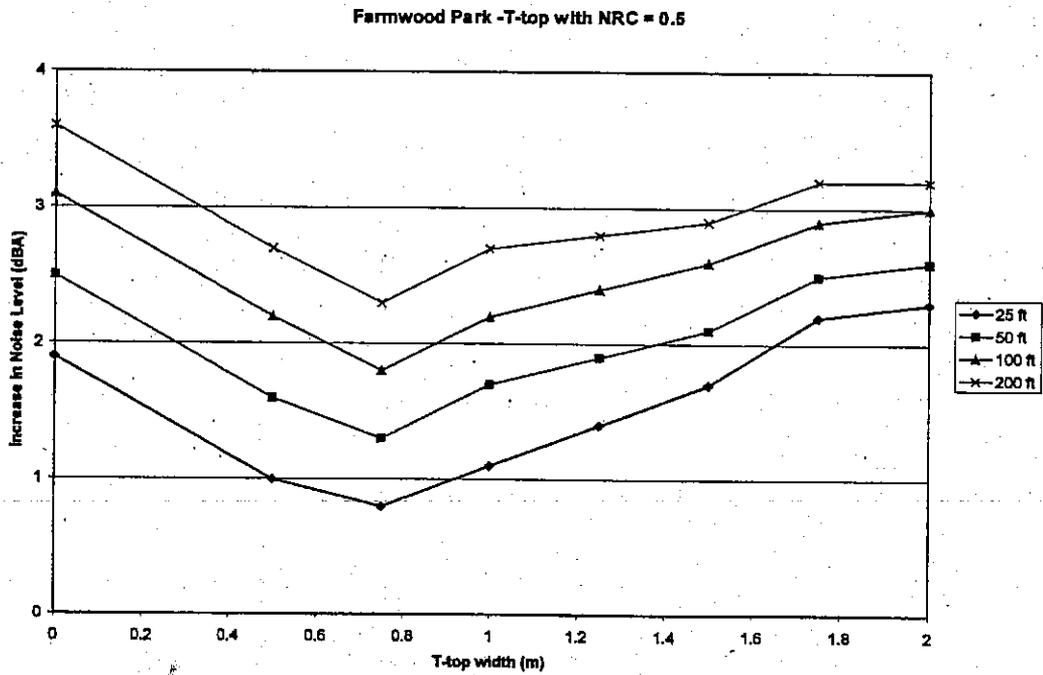


Figure 4-10 TNM parallel barrier analysis for a T-top treatment - Farmwood Park Absorptive - NRC = 0.5.

Another problem with using the parallel module to evaluate the effectiveness of top treatments is that when the barrier height is increased the noise level is predicted to increase. It is desirable to relate the effectiveness of a top treatment to an equivalent increase in barrier height without a top treatment. Yet, increasing the barrier height in the parallel barrier module results in a steady increase in noise level. However, it would be possible to predict the noise level reduction with the main TNM analysis.

The apparent failure of the parallel barrier module to predict the effectiveness of top treatments is not unexpected. The parallel barrier module is intended to predict the increase in noise due to multiple reflections. It is a ray tracing routine that focuses on the echoes reflecting in the canyon created by the parallel barriers. Even though the module allows the barrier profile to be represented, the parallel barrier module does not utilize a diffraction analysis. Instead the barrier profile is only to accurately predict the noise reflections from the barrier. Diffraction is predicted in the primary TNM analysis and the parallel barrier predicted noise increases are used as a noise level adjustment factor at individual receivers.

With the failure of both TNM and STAMINA to predict the effectiveness of top treatments, how should their effectiveness be predicted for sites in the state of Illinois. The researchers of top treatments have utilized three techniques to predict effectiveness: BEM or FEM, scale model testing, and full-scale testing. The scale model testing and full-scale testing are useful for verification of prediction means, but are not appropriate to design or selecting an appropriate top treatments for use in Illinois. The numerical routines based on BEM or FEM are the most flexible, but still require a significant effort to design a reasonable top treatment. A design study may take anywhere from multiple weeks to many months depending on the number of variations that are considered. Each design configuration may require a couple days to analyze and examine the predicted noise level intensities (each frequency is analyzed separately and they are combined as a spectrum for each receiver). In using a numerical method for noise sites in Illinois it is important to represent the relative relation between the noise sources and the receivers.

Access to appropriate BEM programs may be difficult. The majority of researchers reporting BEM predictions for traffic noise studies are using self written programs or one written by fellow traffic noise researchers. A number of the top treatment studies used BEM analyses developed by Chandler-Wilde, Brunel University, Uxbridge, UK. We attempted to contact Professor Chandler-Wilde by email to request use of his BEM analysis. No response was received after two months. We have not exhausted all means to acquire an appropriate BEM program, but it may require some creativity and a significant effort.

4.5 Summary and Conclusions

The area of top treatments is still relatively new and the majority of the studies have been theoretical or scale-models. Very few studies have been done at full-scale and only a portion of these have used actual traffic as the noise source. Thus, it is difficult to make definitive conclusions or recommendations.

The research team feels that the top treatments that may be worth considering for use in

Illinois are either T-top or multiple edge barriers [Watts 1996]. The T-top has the potential to reasonably increase insertion loss while not seriously complicating the barrier design nor introducing concerns with trapped water freezing. The T-top should have an absorbing top surface to maximize the insertion loss and offset the added cost. However, the absorbing top may be damaged due to freezing and thawing. The multiple edge treatment suggested by Watts is attractive without some of the concerns of the T-top treatment. The multiple edge could be retrofitted to an existing barrier or installed on a new barrier. There should be no concern with trapped water or any degradation due to freezing and thawing. The only foreseeable damage might come from debris distorting the added panels.

The effectiveness of a top treatment is site dependent. For example, the Noise Reducer top treatment tested for CAL-DOT showed meager improvement, but this was for an at-grade highway. It may have shown greater improvement for a fill section or elevated highway, where the diffraction path to the observers was large. Top treatments have been widely used on Japanese highways in urban areas, where elevated highways are common. With the elevated highway, moving the first diffraction edge closer to the traffic noise source can significantly increase the diffraction path length. If the highway is on grade, the same change in diffraction edge may have only a minor increase in diffraction path length.

Predicting the improved effectiveness of top treatments is not refined to the point where top treatments can be selected easily. The reported top treatment analyses have been in the research phase and the analyses are not readily available.

Overall, the project team feels it is premature to consider implementing top treatments at this time. Additional research is needed to quantify the improvements that might be expected from top treatments.

Chapter 5 Aids for Communicating Traffic Noise Issues with General Public

The topic of traffic noise and its abatement is a complex topic. There are many complex issues that interact. What may seem like a simple question like "why is the traffic noise so loud" is actually relatively complex. In addition, Tax payers in a community help fund noise barrier walls and highway projects. This puts state DOT personnel on the "firing line" during public hearings or during face-to-face conversations to provide simple but accurate answers to difficult questions. Thus, one part of this project was to develop a means to discuss traffic noise and barriers with the general public.

5.1 Means to Discuss Noise Barriers with the General Public

The topic of traffic noise is complex as well as technical, so the means to discuss traffic noise with the general public should accommodate these difficulties. The goal of this means is to simply present the topic of traffic noise and to provide supplementary education where appropriate. The study team chose to use a home page, hypertext format in addition to a standard tri-fold brochure. The home page format was selected because of its flexibility to integrate text, graphics, and animations. It allowed the user to easily skip subjects that they understood adequately or to go deeper in areas that were of greater interest. Also, the home page format can be updated and modified to meet future requirements. In addition, a tri-fold brochure was developed for use in one-on-one discussions and as a handout at public meetings.

5.1.1 Home Page - Hypertext Traffic Noise Guide

A wide range of traffic noise information was arranged using a home page format. The home page and its hypertext capabilities allow the information to be organized for quick review and allows the users to seek out the information that is of most interest. Users can use the introductory material to gain information quickly, or they can delve deeper in selected topics. The contents of the home page system are detailed in the Appendix.

The information was arranged in a logical sequence with many graphic illustrations. In a few situations, animations were used, e.g., to illustrate wave propagation phenomena. The text explanations use simple straightforward language and were kept to a minimum. The home page format allows this tool to be expanded and updated with ease. This is essential to keep the tool fresh and effective. The reactions from the viewing audience can be used as guidance for future modifications.

The home page traffic noise tool covers essential topics in traffic noise. The document starts with a general introduction to the acoustics and noise. Next, the specific details about traffic noise are presented. This includes traffic noise sources and traffic parameters influencing traffic noise propagation. Then the topic of traffic noise abatement is detailed. Included are typical types of traffic noise abatement means: berms and noise walls.

Even though this educational communication tool was developed using a home page format,

it does not have to be delivered through the Internet. While the delivery will require a computer, it can be installed on a stand-alone computer. IDOT could decide to deliver this information on the Internet. The decision about delivery can be made at a latter date and it can be modified as appropriate.

5.1.2 Tri-Fold Brochure

In addition to the computer-based interactive communication tool, a tri-fold brochure was developed. This brochure can be used as a handout at public meetings as well as a visual aid for one-on-one discussions. The brochure fills in the gaps where it is inappropriate or inconvenient to use the computer-based tool. The brochure is essentially all figures with very few words. It is not intended as a stand-alone document. It is expected that an explanation would come from a public meeting or individual discussion. The brochure is contained in the Appendix.

The brochure was developed in MS Word'97 using selected graphical images from the home page tool. By developing the brochure in a common word processor, it can be updated and refreshed periodically as needs and concerns change.

Chapter 6 Summary

This study has investigated the current state of art relative to traffic noise prediction and top treatments. The findings are as follows. In addition, this study has uncovered many unanswered questions that might be addressed in future research projects. They are included here as part of the summary.

6.1 Summary and Recommendations

The evaluation of traffic noise prediction means is detailed in Chapter 3. The conclusions and recommendations are

- The TNM 1.0 program has many new features to attempt to accurately represent the site between the highway and the observers. These new features also increase the complexity of modeling a highway site to access traffic noise impacts.
- The field measurements at four sites with noise barriers showed that TNM predicted measured noise levels more accurately than STAMINA 2.0. In general STAMINA over predicted the noise levels relative to the measured traffic noise levels.
- Based on these findings, IDOT should start using TNM for future traffic noise impact studies. The TNM program is a complex program, so IDOT should train their noise professionals in use of the program and they should expect to purchase appropriate updated computers.

Top treatments for noise barrier walls is reviewed and evaluated in Chapter 4. The conclusions and recommendations are.

- The state of research and development of top treatments for noise barrier walls is not yet sufficiently refined for general application. The top treatment literature contains mostly theoretical research projects. There have been only a limited number of field demonstrations with inconsistent results. Thus, it is recommended that IDOT continue to monitor development of top treatments. It is likely that some time in the future top treatments will be adequately developed to be considered for use in the state of Illinois.

6.2 Potential Future Studies and Unanswered Questions

This study has uncovered a few questions that could be pursued in future traffic noise studies. Many of these questions concern the recently released FHWA TNM 1.0 traffic noise analysis program.

- Ground Zone Influence - The features in TNM to model sites should be systemically characterized to better understand their impact on predicted noise levels. The current study examined some of these features in an incomplete fashion. Specifically, ground zones should be examined in greater detail. Ground zones can have significant influence

on predicted noise levels and were associated with the unexpected behavior noted at Maple Street. Field measurements and TNM analyses are required to evaluate the interaction between hard and soft ground types. The study should utilize multiple receivers at the same distance from a barrier, as well as similar geometry without a barrier.

- **Height Limits of TNM** - The spatial distribution of noise behind barriers, or the shadow zone, should be systemically studied. The current study considered receivers at heights of 5 ft only, yet there are significant differences between TNM and STAMINA when the receivers are significantly above the ground. The analysis programs would be used to provide guidance regarding selecting appropriate heights above the ground. These study heights may be on the order of 30 ft and would require designing an appropriate means to support a microphone and adjust its height.
- **Distance Limits of TNM** - The TNM program should be tested to assess the region of applicability. It is well recognized that STAMINA is only reasonably accurate up to 300 ft and should not be used beyond 500 ft from highway traffic noise sources. This limit is partly due to STAMINA not including any environmental effects that would be essential for longer distances. The TNM model should be evaluated at longer distances to assess its accuracy. The study team has noticed that TNM indicates insertion losses over 5 dBA at 1000 ft behind a barrier. An assessment of the accuracy of TNM at extreme distances is an essential step in developing guidelines for using TNM.
- **Influence of Wind and Environmental Factors** - The environmental modeling in TNM and the influence of wind direction and velocity should be studied. Wind does not directly influence the design of noise barriers, but it does impact field measurements. The influence of wind is significant; Watts and Morgan [1996] indicated a sensitivity of 1 dBA per m/s for wind velocity perpendicular to the barrier.

REFERENCES

- Anderson, Grant A.; Lee, C.; Fleming, G.; and Menge, C., *FHWA Traffic Noise Model (FHWA TNM), Version 1.0; User's Guide* FHWA-PD-96-009 and DOT-VNTSC-FHWA-98-1, January 1998.
- Barboza, Michael J.; Carpenter, Sharon P.; Roche, Leslie E., "Prediction of traffic noise: a screening technique." *J. Air & Waste Management Ass.* 45, pp 703-708, Sept 1995.
- Bartolini, Buggero; Bisio, Giacono; and Magrin, Ugo, "The acoustic mapping of Genoa - the relative weight of the various noise sources and the spatial distribution of outdoor noise levels." *Noise Control Eng. J.* 54(1), pp 9-15, Jan-Feb 1990.
- Barry, T.M.; and Reagan, J.A., *FHWA Highway Traffic Noise Prediction Model*, FHWA-RD-77-108, USDOT, December 1978.
- Beranek, Leo L. and Ver, Istvan L., *Noise and Vibration Control Engineering - Principles and Applications*. John Wiley & Sons, Inc. 1992.
- Berengier, Michel C.; and Anfosso-Ledee, Fabienne, "State-of-the-art prediction and control of road traffic noise in France" *Transportation Research Record 1626* pp 71-77, Transportation Research Board Washington D.C., 1998.
- Berge, Truls, "Vehicle-noise-emission limits - influence on traffic noise levels past and future." *Noise Control Eng. J.* 42(2), pp 53-58, Mar-Apr 1994.
- Bolt, Beranek, and Newman, *Highway Noise Generation and Control*, NCHRP report 173, TRB, 1976.
- Boulanger, Patrice; Waters-Fuller, Tim; Attenborough, Keith; and Li, Lai Ming, "Models and measurements of sound propagation from a point source over mixed impedance ground." *J. Acoustical Society of America* 102(3), pp 1432-1442, Sept 1997
- Bowlby, W.; Wayson, R.L.; Chiguluri, S.; Martin, M.; and Herman, L.A., *Interrupted Flow Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model*, FHWA-PD-97-019, USDOT, January 1997.
- Bowlby, William, *In-Service Experience with Traffic Noise Barriers*, NCHRP Synthesis 181, TRB, 1992
- Bowlby, William; Cohn, Louis F.; Harris, R.A., "A review of studies of insertion loss degradation for parallel highway noise barriers." *Noise Control Eng. J.* 28(2), pp 40-53, March-April 1987.

- Bowlby, William; and Cohn, Louis F., *Sound-Absorptive Highway Noise Barriers*, FHWA-TS-86-214, May 1986.
- Bowlby, W; Higgins, J.; and Reagan, J., *Noise Barrier Cost Reduction Procedure, STAMINA 2.0/OPTIMA: Users Manual* FHWA-DP-58-1, April 1982.
- Bowlby, William, *Sound Procedures for Measuring Highway Noise: Final Report*. FHWA-DP-45-1R USDOT, August 1981.
- Chessell, C.I., "Propagation of noise along a finite impedance boundary." *J. Acoustical Soc. Am.* 62(4), pp 825-834, Oct 1977.
- Cohn, Louis F.; Harris, Roswell A.; Rolfer, Ronald L.; Duncan, Darin L.; and Woosley, Robert L., "Special noise barrier applications." *Transportation Research Record* No. 1416, pp 69-74, 1993.
- Cohn, Louis F., *Highway Noise Barriers*, NCHRP Synthesis of Highway Practice 87, TRB December 1981.
- Cremers, L.; Fyfe, K.R.; and Coyette, J.P., "A variable order infinite acoustic wave envelope element." *J. Sound and Vibration* 171(4), pp 483-508, 1994.
- Crombie, D.H.; Hothersall, D.C.; and Chandler-Wilde, S.N., "Multiple-edge noise barriers." *Applied Acoustics* 44(4), pp 353-367, 1995.
- Crombie, D.H.; and Hothersall, D.C., "The performance of multiple noise barriers." *J. Sound and Vibration* 174(4), pp 459-473, 1994.
- Coyette, J.P.; and Fyfe, K.R., "An improved formulation for acoustic eigenmode extraction from boundary element models." *J. Vibrations and Acoustics* 112(3), pp 392-398, July 1990.
- Creasey, F. Thomas; Agent, Kenneth R., "Effectiveness of traffic noise barrier on I-471 in Campbell County, Kentucky." *Transportation Research Record* 1176, pp 5-12, 1988.
- Daigle, G.A., et al. "Technical Assessment of the Effectiveness of Noise Walls", I-INCE publication 98-1, Draft Report, Noise/News International, pp 11-35, March 1998.
- De Jong, B.A.; Moerkerken, A.; and Van Der Torn, J.D., "Propagation of sound over grassland and over an earth barrier." *J. Sound and Vibration* 86(1), pp 23-46, 1983.
- Dezelak, F., "Calculation of additional dimensions of noise barriers with insufficient noise reduction." *Proceedings of Internoise 96*, pp 775-778, 1996.

- Embleton, T.F.W.; Piercy, J.E.; and Daigle, G.A., "Effective flow resistivity of ground surfaces determined by acoustical measurements." *J. Acoustical Society of America* 74(4), pp 1239-1244, Oct 1983.
- Federal Highway Administration, *Noise Fundamentals Training Document - Highway Noise Fundamentals*. USDOT, September 1980.
- Fleming, Gregg G.; Rapoza, Amanda S.; Lee, Cynthia S.Y., *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM), Version 1.0*, FHWA-PD-96-008, USDOT, November 1995.
- Fleming, Gregg G.; and Rickley, Edward J., *Performance Evaluation of Experimental Highway Noise Barriers*, FHWA-RD-94-093/DOT-VNTSC-FHWA-94-16, April 1994.
- Fujiwara, Kyoji; Hothersall, David C.; Kim, Chul-Hwan, "Noise barriers with reactive surfaces." *Applied Acoustics* 53(4), pp 255-272, 1998.
- Fyfe, K.R., "Acoustic modeling of road noise barriers"
<http://www.mece.ualberta.ca/staff/fyfe/RoadNoise/BarrierModeling.html>, 1998.
- Gharabegian, Areg, "Improving the performance of highway soundwalls." *Sound and Vibration*, pp 30-33, July 1996.
- Guidelines for Evaluating the Performance of Highway Sound Barriers*, HITEC 96-04, Product 24, October 1996.
- Guo, Jingnan; and Pan, Jie, "Application of active noise control to noise barriers." *Acoustics Australia* 25(1), pp 11-16, April 1997.
- Harris, Roswell A.; Cohn, Louis F.; and Grant, C.D., "Using the STAMINA 2.0 computer program to calculate contours of one-hour-average sound levels from highway traffic noise." *Noise Control Eng. J.* 43(5), pp 173-179, Sept-Oct 1995.
- Ho, Steve S. T.; Busch-Vishniac, Ilene J.; and Blackstock David T., "Noise reduction by a barrier having a random edge profile" *J. Acoustical Society of America* 101(5), pp. 2669-2676, May 1997.
- Houdt, J.J.; Goeman, Th.; Breugel, Th.P.A.; and Springborn, M., "Influence of road surface on traffic noise: a comparison of mobile and stationary measuring techniques." *Noise Control Eng. J.* 41(3), pp 365-370, Nov-Dec 1993.
- Ishiyanna, Takeshi; Tateishi, Kazannasa; and Arai, Toshihiro, "An analysis of traffic noise propagation around main roads in Tokyo." *Noise Control Eng. J.* 36(2), pp 65-72, March-April 1991.

- Jung, F.W.; Blaney, C.T., "Highway traffic noise prediction for microcomputers: modeling of Ontario simplified program." *Transportation Research Record 1176*, pp 41-51, 1988
- Klingner, Richard E.; Busch-Vishniac, Ilene; McNerney, Michael T.; Ho, Steve; and Peron, Ronald, *Effective Noise Barrier Solutions for TxDOT: A First-Year Progress Report*, Research Report 1471-1 Center for Transportation Research, The University of Texas at Austin, February, 1996.
- Kugler, B. Andrew; and Piersol, Allan G., *Highway Noise: A Field evaluation of Traffic Noise Reduction Measures*, NCHRP report 144, TRB 1973.
- Lee, Cynthia S.Y.; and Fleming, Gregg G., *Measurement of Highway-Related Noise*. FHWA-PD-96-046 and DOT-VNTSC-FHWA-96-5, May 1996.
- Lee, Van M.; Michalove, Robert A.; and Slutsky, Simon, "Tilted Parallel barrier program: application and verification." *Transportation Research Record 1176*, pp 23-33, 1988.
- Makarewicz, Rufin, "A simple model of outdoor noise propagation." *Applied Acoustics* 54(2), pp 131-140, 1998.
- Makarewicz, Rufin, "Influence of ground effect and refraction on road traffic noise." *Applied Acoustics* 52(2), pp 125-137, 1997.
- Manning, J.E.; and Blair, C.N., *Field Study of a Variable-Height Highway-Noise Barrier* DOT-TSC-NHTSA-78-23, March 1978.
- Menge, Christopher W.; Rossano, C. F.; Anderson, Grant S.; and Bajdek, C. J., *FHWA Traffic Noise Model (FHWA TNM), Version 1.0 Technical Manual*, FHWA-PD-96-010 DOT-VNTSC-FHWA-98-2, February 1998.
- Muradali, A.; and Fyfe, K.R., "A study of 2D and 3D barrier insertion loss using improved diffraction-based methods." *Applied Acoustics* 53(1-3), pp 49-75, 1998.
- Nielsen, Leif, "International standards for acoustics and noise control." *Noise Control Eng. J.* 32(2), pp 67-72, Mar-Apr 1989.
- Okubo, Tomonao; and Fujiwara, Kyoji, "Efficiency of a noise barrier with an acoustically soft cylindrical edge." *J. Acoustical Society of Japan(E)* 19(3), pp 187-197, 1998.
- Parsons Engineering Science, Inc. *NoiseReducier Noise Performance Report, for Nichimen American, Inc.* December 1994

- Romick-Allen, R. K.; Lin, Chiang; Morgan, Susan M.; and Bruns, Michael T.; "Fitting the TNM REMELs for use in STAMINA 2.0" *Proceedings of Transportation Research Board 78th Annual Meeting*, Washington D.C., Paper 99-0471, January 10-14, 1999.
- Rosenberg, Eric; Busch-Vishniac, Ilene J., "Continued investigation of noise reduction by a random-edge noise barrier", *Acoustical Society of America 133 Meeting Lay Language Papers* URL: www.acoustics.org/133rd/2pnas4.html, June 1997.
- Rudder, F.F.; Lam, D.F.; and Chueng, P., *User's Manual: FHWA Level 2 Highway Traffic Noise Prediction Model STAMINA 1.0*, FHWA-RD-78-138, USDOT, May 1979.
- Salomons, Erik M.; and Geerlings, Alex C., "Comparison of a ray model and a Fourier-boundary element method for traffic noise situations with multiple diffractions and reflections." *Acta Acustica* 83, pp 35-47, 1997.
- Shao, J.; Sha, J.-Z.; and Zhang, Z.-L., "The method of the minimum sum of squared acoustic pressures in an actively controlled noise barrier." *J. Sound and Vibrations* 204(2), pp 381-385, 1997.
- Shima, H.; Watanabe, T.; Mizuno, K.; Lida, K.; Matsumoto, K.; and Naksdski, K., "Noise reduction of a multiple edge noise barrier." *Proceedings of Internoise 96*, pp 791-794, 1996.
- Slutsky, Simon; and Bertoni, Henry L., "Analysis and programs for assessment of absorptive and tilted parallel barriers." *Transportation Research Record* 1176, pp 13-22, 1988.
- State of Illinois, *Control of Noise from Motor Vehicles*, IIEQ document 74-42, June 1974.
- Watts, G.R., "In Situ method for determining the transmission loss of noise barriers." *Applied Acoustics* 51(4), pp 421-438, 1997.
- Watts, G.R.; "Acoustic performance of a multiple edge noise barrier profile at motorway sites." *Applied Acoustics* 47(1), pp 47-66, 1996.
- Watts, G.R.; Morgan, P.A., "Acoustic performance of an interference-type noise-barrier profile." *Applied Acoustics* 49(1), pp 1-16, 1996.
- Watts, G.R.; Crombie, D.H.; and Hothersall, D.C., "Acoustic Performance of new designs of traffic noise barriers: full scale tests." *J. Sound and Vibration* 177(3), pp 289-305, 1994.

Appendix A

THE NATURE OF SOUND

In order to understand traffic noise barrier walls, it is necessary to understand the basics of sound.

WHAT IS SOUND?

Sound is pressure waves. That is, changes in air pressure. Our ears "hear" by detecting the pressure that is traveling past them.

HOW DOES SOUND TRAVEL?

Sound travels in a sphere away from its point of origin. Imagine a stone that is thrown in a pond. The water ripples away from where the stone lands in the pond. The same is true for sound. Sound waves "ripple" away from the source of the sound.

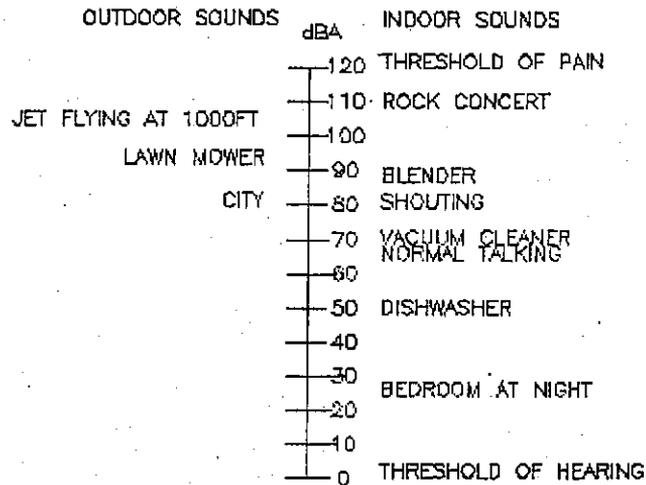
HOW IS SOUND MEASURED?

Sound is measured in decibels (dB). The decibel scale is a logarithmic scale; it is not linear. This means that two equal sounds occurring at the same time do not sound twice as loud as just one of the sounds.

$$dB = 10 \text{ LOG} \left(\frac{P}{P_0} \right)^2$$

Humans are not able to hear all sounds. The dB scale is a measure of all sounds, even those that humans cannot hear. In order to simplify the dB scale, sounds can be measured on an A weighted scale (dBA). The A weighted scale is used to represent the way humans hear sounds. Here are some typical sounds as measured on the A weighted scale.

THE NATURE OF SOUND



There are also some statistical methods to measure sound. L10, L50, L90, and Leq are a few examples of statistical methods to describe the time varying aspect of sound. Leq, for example, measures the equivalent (average) sound over a specific time increment. L10 measures the sound that is present 10 percent of the time. L50 and L90 represent the sound that is present at 50 and 90 percent of the time respectively.

THE BASICS OF HUMAN HEARING

Human ears can hear a wide range of frequencies. However, our ears hear only a small portion of the sounds that are present. An average young adult can hear a range of frequencies between 20Hz and 20,000Hz. Frequencies below 20Hz are known as infrasound, and frequencies greater than 20,000Hz are known as ultrasound.

The frequency (pitch) at which a sound occurs affects the way in which we perceive the sound. In general, high frequency sounds are more disturbing than low frequency sounds.

Background sound also affects our hearing. Examples are sounds from a television when trying to talk on the phone, or the humming of the computer. These sounds can interfere with our hearing.

The human ear can hear a wide range of sound intensity. However, the human ear cannot easily discriminate small changes in sound levels. A 3 dBA increase is barely noticeable even though the sound source was doubled.

ABILITY TO DISCRIMINATE BETWEEN SOUND LEVELS	
INCREASE IN dB	ABILITY TO DETECT A DIFFERENCE
2-3	JUST BARELY
5	NOTICEABLE
10	TWICE AS LOUD
40	EXTREME DIFFERENCE

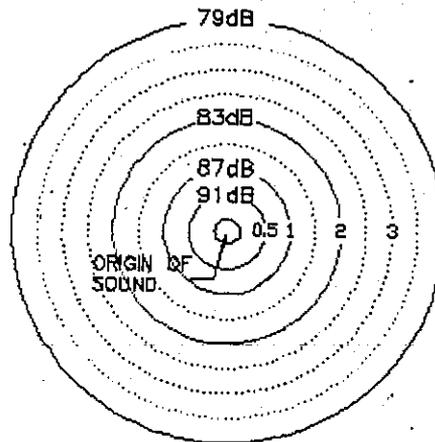
INTERACTION OF SOUND WITH THE ENVIRONMENT

Sound dissipates(attenuates) as it travels. Since sound travels in a sphere, its energy spreads. The farther away from the original sound source, the less energy there is,so the fainter the sound. The area of the sphere is :

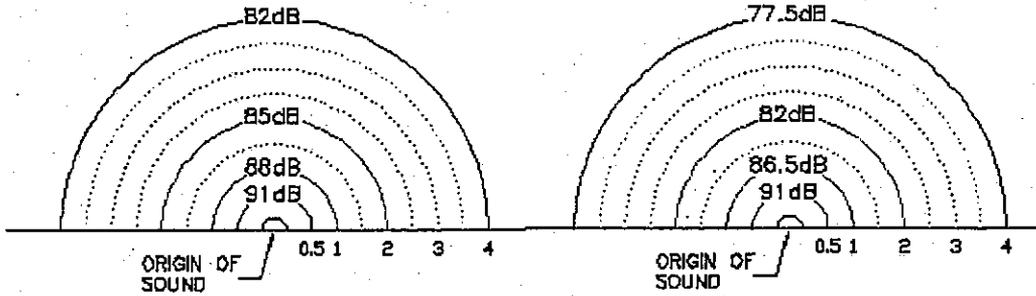
$$A = 4\pi r^2$$

where r is the distance from the sound. So, if the distance from the sound source is doubled, the sound is reduced by one fourth. The ground surface plays a key role in how fast the sound dissipates. Hard acoustic surfaces, such as parking lots and lakes, reflect sound. This means that the reduction of sound through distance decreases. Soft surfaces on the other hand absorb sound. This means that the sound reduction through distance is increased.

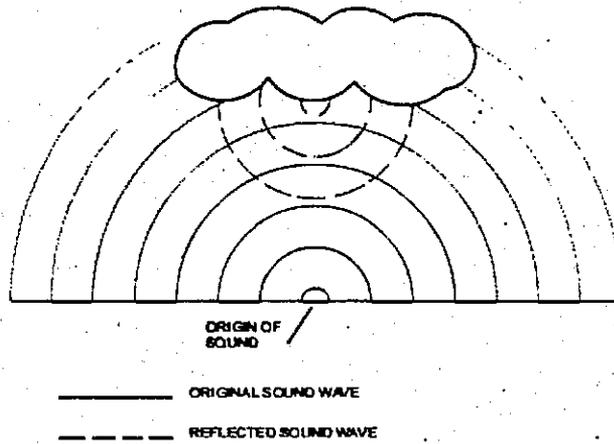
REDUCTION OF SOUND THROUGH DISTANCE



REDUCTION OF SOUND THROUGH DISTANCE FOR A HARD SURFACE
 REDUCTION OF SOUND THROUGH DISTANCE FOR A SOFT SURFACE



Environmental conditions also affect how sound dissipates. Clouds tend to reflect sound back toward the earth therefore sound increases.



Rain tends to increase the high frequency sounds, such as tires passing over pavement. Snow, on the other hand, tends to reduce sound propagation.

THE NATURE OF SOUND

EFFECT OF ATMOSPHERIC CONDITIONS ON SOUND	
ATMOSPHERIC CONDITION	EFFECT ON NOISE
RAIN	INCREASE OF HIGH FREQUENCIES
SNOW	LOWERS NOISE PROPAGATION
WITH WIND	NO EFFECT
AGAINST WIND	LOWERS NOISE PROPAGATION

Concern Over Traffic Noise

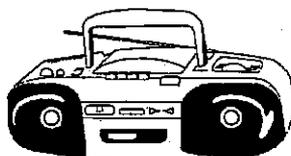
Traffic Noise Characteristics

Barrier Walls for Traffic Noise Reduction

CONCERN OVER TRAFFIC NOISE

NOISE IS SUBJECTIVE

Sound affects each person differently. Sounds that bother some people may not bother others. Background sound is also subjective.



Oh Dear!

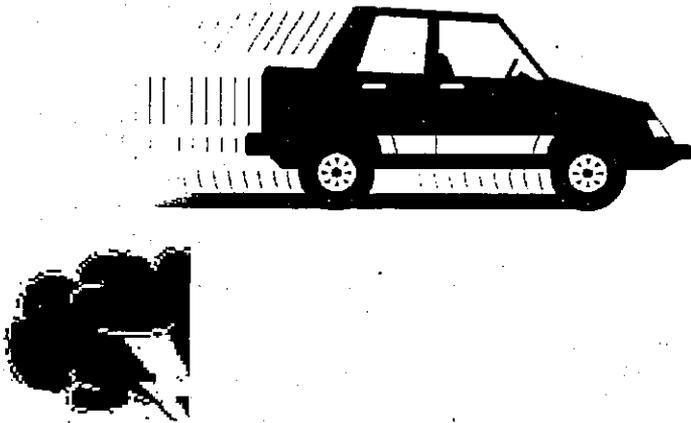


The frequency of occurrence of the sound also plays a role in how it is perceived. An airplane passing overhead once a day may not be as bothersome as 50 airplanes passing over in a day's time.

TRAFFIC NOISE IS NOT CONSIDERED A NATURAL PART OF OUR ENVIRONMENT

Traffic noise is not a "natural" sound. We don't think of traffic noise the same way that we think of birds chirping, trees rustling, or thunderstorms.

CONCERN OVER TRAFFIC NOISE



VS.

The Nature Of Sound
Traffic Noise Characteristics
Barrier Walls for Traffic Noise Reduction

TRAFFIC NOISE CHARACTERISTICS

SOURCES OF TRAFFIC NOISE

There are four main sources of traffic noise:

1. Tires on pavement
2. Exhaust
3. Engines and gear boxes
4. Aerodynamics of vehicles

Tires on pavement

Tires tend to make a high frequency sound as they pass over a pavement. The faster the car is traveling, the more sound there will be from the tires. The sound of tires on pavement is a significant source of traffic noise.

Exhaust

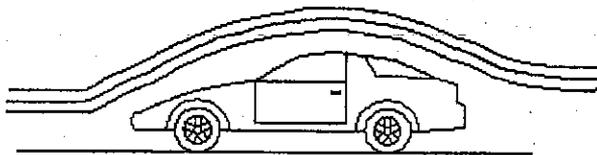
Engine exhaust systems are a primary source of traffic noise. Every vehicle produces exhaust noise. Faulty mufflers produce excessive noise. Heavy trucks have relatively high exits from their exhaust.

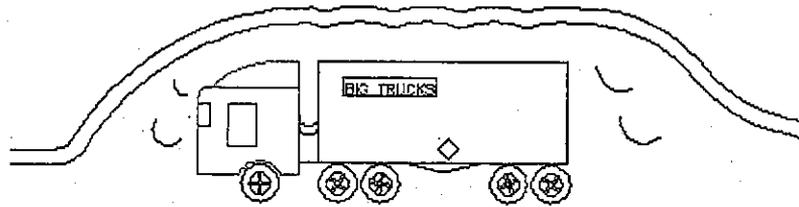
Engines and gear boxes

Engines and gear boxes are a moderate contributor to traffic noise. Engine noise increases when accelerating or when going up hill. In general, diesel engines produce more noise than gasoline engines.

Aerodynamics of vehicles

The vehicle's aerodynamics is another source of sound. The less a vehicle disturbs the air by its passing, the less sound it generates. This is a minor source of traffic noise.





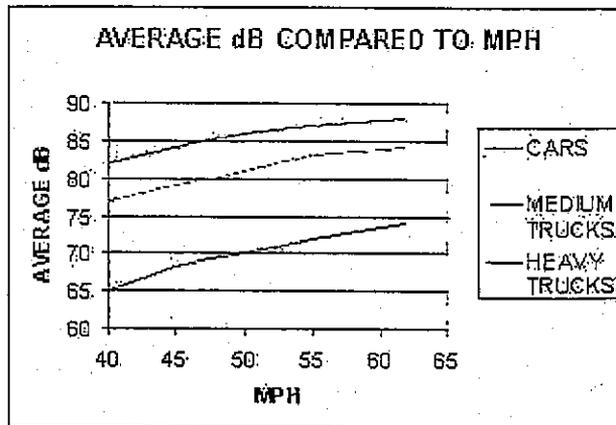
AMOUNT OF TRAFFIC NOISE

The amount of traffic noise depends on three traffic variables:

1. The speed of vehicles
2. The volume of traffic
3. The type of vehicles

Speed of vehicles

The faster the vehicle travels, the more noise it produces. This is due to the tires and the aerodynamics of the vehicle.



Volume of traffic

Assuming the traffic speed remains the same, the more traffic there is the more noise there will be. However, when traffic slows down, tire noise is reduced. Traffic noise does not add linearly. Doubling the number of sound sources does not lead to a doubling of sound.

To better illustrate this concept, try tapping a pencil on a table. Then tap two pencils. The sound you hear is not twice as loud, but you should be able to detect a difference.

TRAFFIC NOISE CHARACTERISTICS

Type of vehicles

Semi tractor trailers make more noise than small cars. The vehicle's tires, exhaust height, engine, gear boxes, and aerodynamics all play a role in producing noise.

The Nature of Sound

Concern Over Traffic Noise

Barrier Walls for Traffic Noise Reduction

BARRIER WALLS FOR TRAFFIC NOISE REDUCTION

There are two general types of noise barriers: walls and berms.

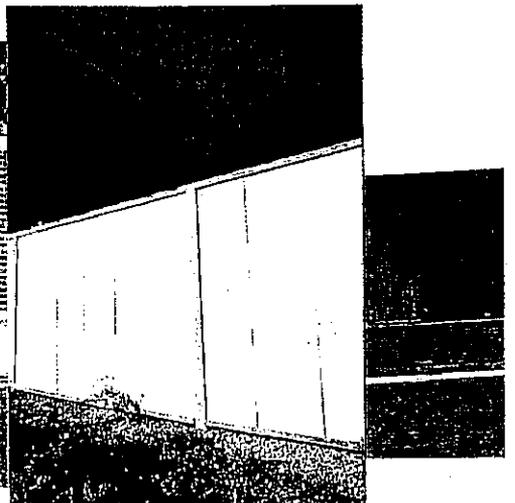
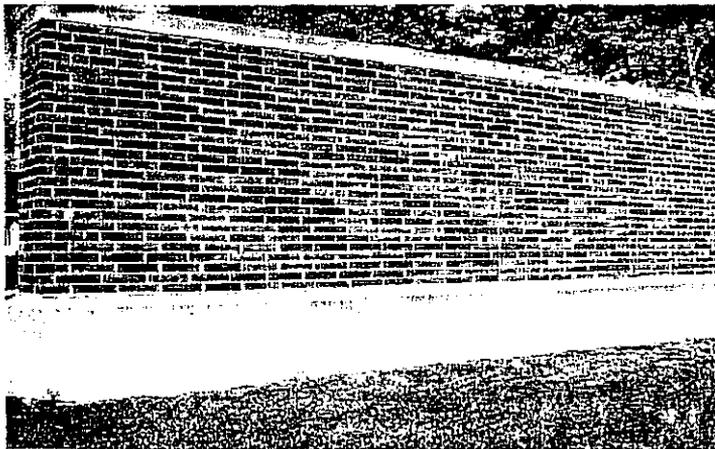
NOISE BARRIER WALLS

What is a noise barrier wall?

A noise barrier wall is any self-supporting structure that is built for the sole purpose of reducing the amount of noise that nearby residents hear.

What do noise barrier walls look like?

Noise barrier walls may come in many forms. They may be made of concrete, wood, metal, brick, or any number of materials. Walls may be built at various heights.



How do noise barrier walls

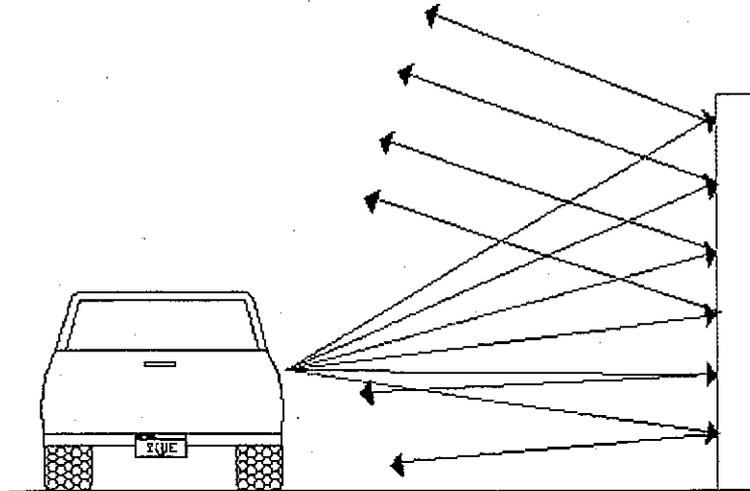
reduce traffic noise?

Noise barrier walls interact with traffic noise in three ways:

1. Reflection
2. Diffraction
3. Absorption

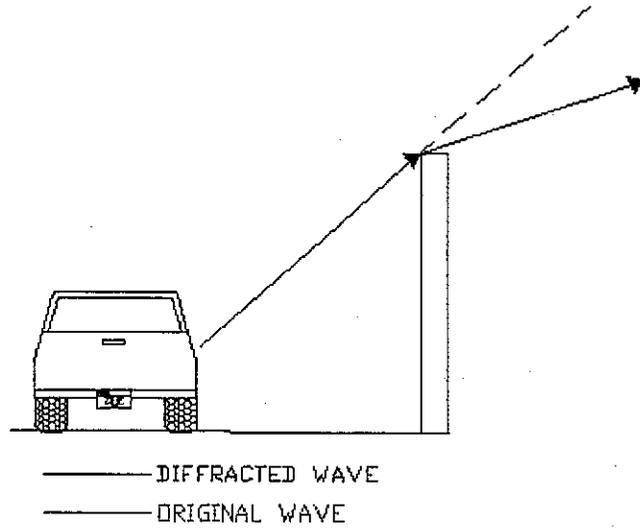
Reflection

Noise barrier walls reflect sound waves away from the wall.



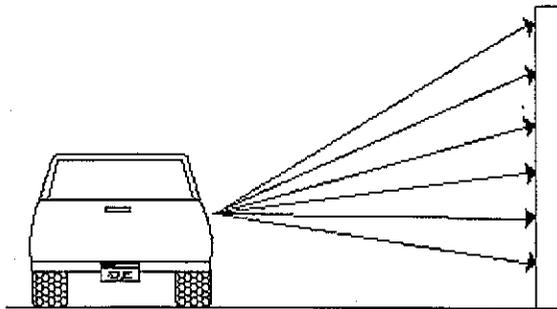
Diffraction

Noise barrier walls also diffract sound over the top of the wall. Diffracted sound waves act as a new sound source that form on the edge of the wall. These sound waves "bend" over the top of the wall and can be heard on the opposite side of the wall.



Absorption

Noise barrier walls may also absorb sound waves, not all walls absorb sound waves. The amount of sound that a wall can absorb depends on the materials the wall is made of. Absorption is frequency dependent and many means to enhance absorption do not weather well and may require maintenance.



How much do noise barrier walls cost?

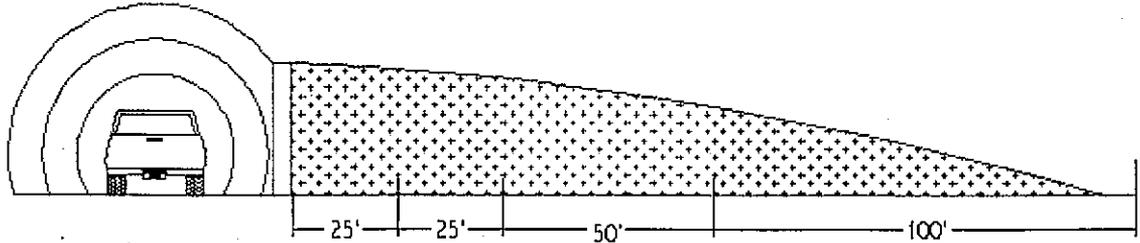
Noise barrier walls typically cost \$1.5 million per mile for a 12' high wall. This cost includes materials and construction, but does not include the cost of maintenance or repairs

How effective are noise barrier walls?

The effectiveness of a noise barrier wall depends on the observer's location relative to the wall, and the height of the wall.

Imagine standing 25' from a highway without a wall. Now imagine a wall is present

right in front of you. There will be a noticeable reduction in noise. Next stand 200' from the highway without a wall. Then imagine the wall is in the same place as before (25' from the highway), the reduction of sound is not as noticeable as before. This does not mean that it is quieter 25' from the highway than 200', it means that at 25' there is a greater benefit from the wall being there.



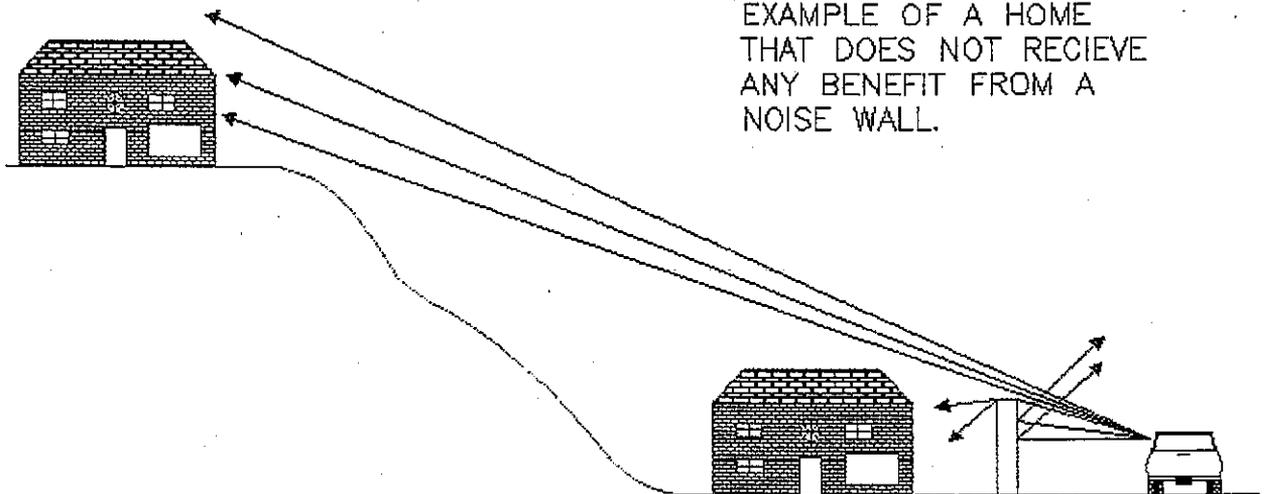
Noise barriers walls will not block all of the sound.

Within the shadow zone.

The shadow zone is the region just behind the wall where the wall is considered to be fully effective, a reduction of 8dB is considered to be fully effective.

Outside the shadow zone.

Outside the shadow zone, the reduction of noise is less obvious. Even a reduction of 3dB is just barely noticeable. In fact, the noise level may increase with an increase in distance from the wall. The diffracted sound waves combined with original sound waves may actually slightly increase the noise level. In general, if the barrier does not break the line of sight, there won't be any decrease in traffic noise.



Berms

What is a berm?

A berm is an earthen "mound" built to reduce traffic noise. Berms require larger land acquisitions than walls do, but they provide about 3dB more noise reduction than walls for the same height.

What do berms look like?



How do berms reduce traffic noise?

Berms reduce traffic noise in the same way that walls reduce noise. Berms (typically a soft surface) absorb, reflect, and diffract sound waves.

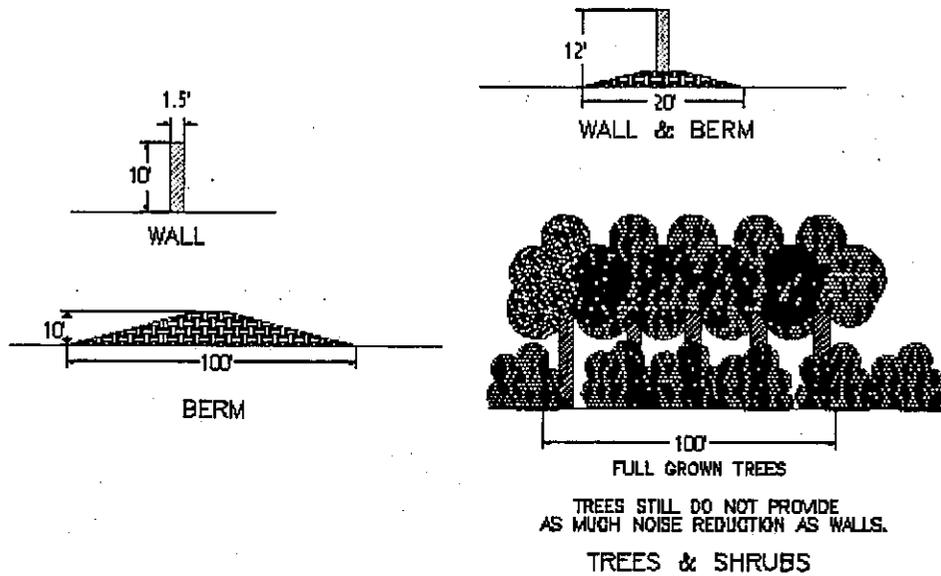
Land space required for walls, berms, and trees

Walls, berms, and trees each require a different amount of land to perform their intended function. Walls require the least amount of land. A typical wall is less than 2' thick. Walls tend to cost less because less land needs to be purchased. Berms require much more land than walls. A typical berm requires 100' of property. A berm that is 100' wide, 10' tall, and 1 mile long, requires about **262,100 TONS** of soil! This increases the cost of a berm compared to a wall. A wall may be combined with a short berm for aesthetic purposes.

BARRIER WALLS FOR TRAFFIC NOISE REDUCTION

Trees and shrubs are not very effective in reducing traffic noise. It takes over 100' of dense trees and shrubs to slightly reduce traffic noise. This is also very expensive, land needs to be purchased and trees and shrubs need to be planted. This method does block the line of sight of the noise source, and therefore provides psychological benefits.

DIFFERENT TYPES OF NOISE BARRIER WALLS AND THE SPACE REQUIRED FOR EACH.



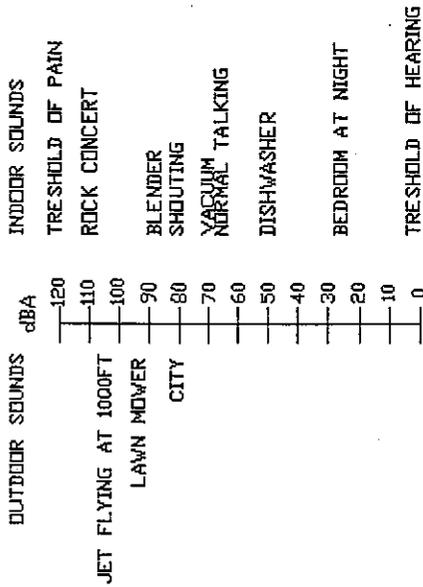
The Nature of Sound
Concern Over Traffic Noise
Traffic Noise Characteristics

Appendix B

**Tri-Fold Brochure - Highway Traffic Noise
Pages B2 and B3**

The Nature of Sound

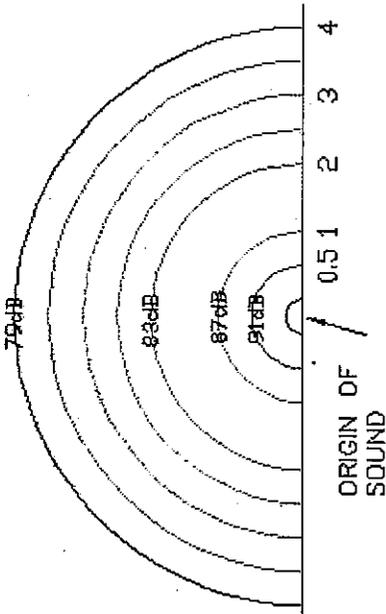
Sound is pressure waves. That is, changes in air pressure. Sound is measured in decibels, on a logarithmic scale. The A-weighted scale is used to represent the way humans hear sounds.



Humans are not able to discriminate between small changes in sound levels.

ABILITY TO DISCRIMINATE BETWEEN SOUND LEVELS	INCREASE IN dB
ABILITY TO DETECT A DIFFERENCE	2-3
JUST BARELY NOTICEABLE	5
TWICE AS LOUD	10
EXTREME DIFFERENCE	40

Sound dissipates as it travels. Sound is reduced by 4 dB for each doubling of distance from the sound source.



Concern Over Traffic Noise

Sound is subjective. Sounds that bother some people, may not bother others. The frequency of occurrence of the sound also plays a role in how the sound is perceived. Traffic noise is not considered to be a natural sound. We don't think of traffic noise the same way we think of birds chirping or the roar of a waterfall.

Traffic Noise Characteristics

There are four main components of traffic noise:

- 1) tires on pavement
- 2) aerodynamics of vehicles
- 3) exhaust
- 4) engines and gear boxes

Tires on pavement

Tires tend to make high frequency sound as they pass over the pavement. This is a significant source of sound.

Aerodynamics of vehicles

Vehicles disturb the air as they pass. This is a minor source of sound.

Exhaust

Engine exhaust systems are a primary source of traffic noise. Heavy trucks tend to make more exhaust noise.

Engines and gear boxes

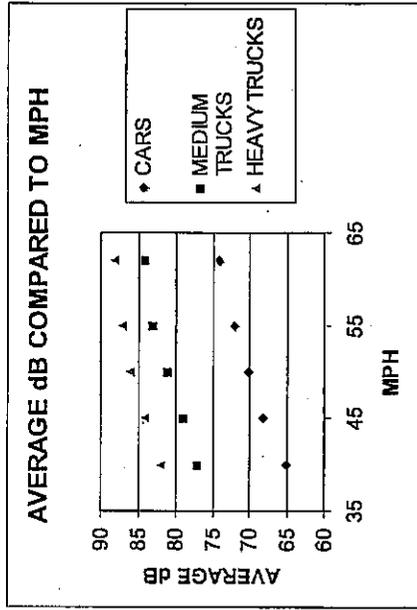
Engine noise tends to increase when accelerating or traveling up-hill. In general, diesel engines produce more noise than gas engines. This is a significant source of traffic noise.

Amount of Traffic Noise

The amount of traffic noise depends on the speed and volume of vehicles.

Speed of vehicles

The faster a vehicle travels, the more sound it produces.



Volume of traffic

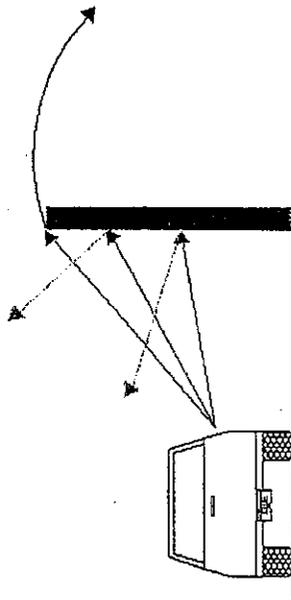
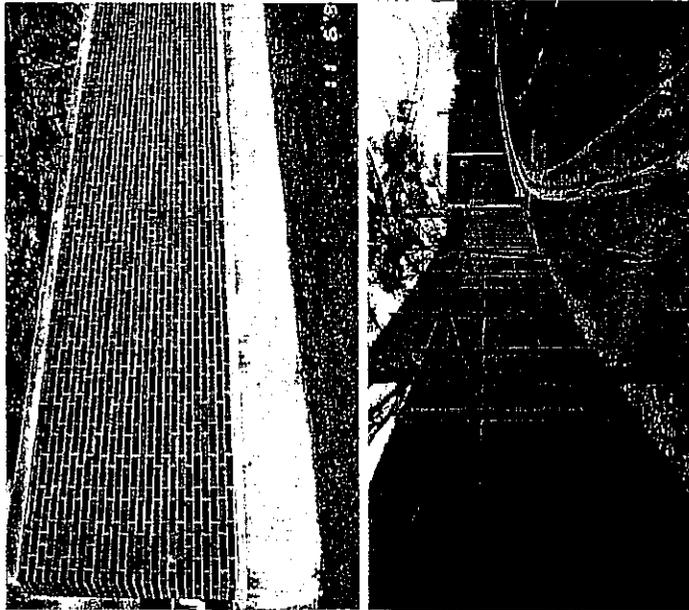
Assuming speed stays the same, the more vehicles there are the more noise there will be. However, when traffic volume increases and speed reduces, tire noise is reduced.

Barrier Walls for Traffic Noise Reduction

Noise barrier walls

A noise barrier wall is any self-supporting structure that is built for the sole purpose of reducing the amount of noise that residents hear.

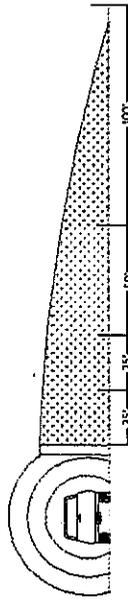
What do noise barrier walls look like?



— Reflected
- - - Original wave
· · · Diffracted

How effective are noise barrier walls?

Noise walls are most effective for those in the shadow zone. That is, the area nearest the wall.



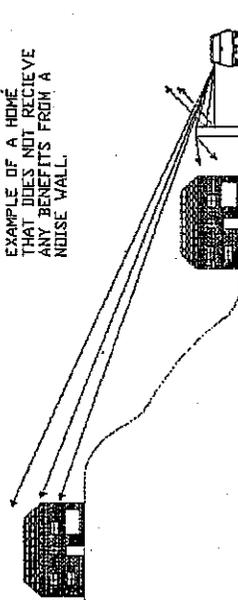
Informational pamphlet concerning traffic noise barrier walls.

Created by:

School of Engineering
Southern Illinois University Edwardsville

1999

EXAMPLE OF A HOME THAT DOES NOT RECEIVE ANY BENEFITS FROM A NOISE WALL.



Berms

Berms are earth mounds built to reduce traffic noise.



How much do noise barriers cost?

Noise barrier walls typically cost \$1.5 million per mile. This includes the cost of materials and construction.

How do noise barrier walls reduce traffic noise?

Noise walls reduce traffic noise in three ways:

- 1) reflection
- 2) diffraction
- 3) absorption