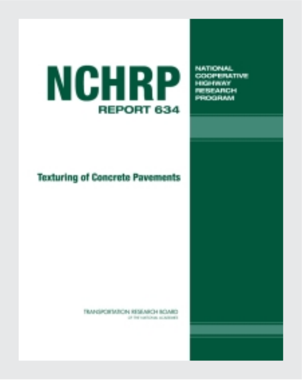


Texturing of Concrete Pavements

DETAILS

97 pages | | PAPERBACK
ISBN 978-0-309-11792-0 | DOI 10.17226/14318

AUTHORS

K L Smith; Jim W Hall; P Littleton; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 634

Texturing of Concrete Pavements

J. W. Hall
K. L. Smith
AND
P. Littleton
APPLIED RESEARCH ASSOCIATES, INC.
Vicksburg, MS

Subject Areas
Materials and Construction

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2009
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 634

Project 10-67
ISSN 0077-5614
ISBN 978-0-309-11792-0
Library of Congress Control Number 2009933398

COPYRIGHT PERMISSION

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

The Transportation Research Board of the National Academies, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

CRP STAFF FOR NCHRP REPORT 634

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
Amir N. Hanna, *Senior Program Officer*
Eileen P. Delaney, *Director of Publications*
Hilary Freer, *Senior Editor*

NCHRP PROJECT 10-67 PANEL

Field of Materials and Construction—Area of Specifications, Procedures, and Practices

Thomas M. Hearne, Jr., *North Carolina DOT, Harrisburg, NC* (Chair)
Brad W. Allen, *New York State DOT, Albany, NY*
James W. Mack, *CEMEX, Houston, TX*
Matthew W. Mueller, *Illinois DOT, Springfield, IL*
Thomas A. Pyle, *California DOT, Sacramento, CA*
J. Jeffrey Seiders, Jr., *Texas DOT, Austin, TX*
John H. Tenison, *AMEC Earth & Environmental, Albuquerque, NM*
Roger L. Wayson, *University of Central Florida, Orlando, FL*
Mark Swanlund, *FHWA Liaison*
Stephen F. Maher, *TRB Liaison*

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents a recommended process for determining the type of concrete pavement texture that should be used for a specific highway project. The process considers the effects of texture type on friction and noise characteristics. The report will guide pavement and construction engineers in identifying and specifying textures for concrete pavements that will provide adequate surface characteristics. The information contained in the report will be of immediate interest to state engineers and others concerned with concrete pavement design and construction.

Tining—a means of texturing newly constructed concrete pavements—is generally performed to enhance pavement-surface macro-texture to improve pavement-surface frictional characteristics and reduce potential for hydroplaning, skidding, and wet-weather crashes. However, there has been a concern that tining has evolved without adequate consideration of the effects on noise generation, long-term durability, smoothness, constructibility, pavement serviceability, and cost-effectiveness. Other options for texturing concrete pavements might provide better performance and yield environmental and economic benefits. Furthermore, no widely accepted guidelines or procedures for identifying and selecting methods of texturing concrete pavements that consider relevant technical, environmental, economic, and safety issues are available. Thus, research was needed to develop a rational procedure for use by highway agency personnel in identifying and selecting texturing methods that will provide adequate surface characteristics for concrete pavements.

Under NCHRP Project 10-67, "Texturing of Concrete Pavements," Applied Research Associates, Inc., worked with the objective of recommending appropriate methods for texturing concrete pavements for specific applications and ranges of climatic, site, and traffic conditions. These methods were to include tining and other means of texturing fresh and hardened concrete so as to enhance surface frictional characteristics. To accomplish this objective, the researchers reviewed available information on methods for texturing concrete pavements; conducted texture, friction, and noise measurements on in-service pavements in 13 states; identified textures likely to provide adequate surface characteristics; and investigated these textures through in-service measurements on specially constructed sections in a paving project. Based on this work, the researchers proposed a process for determining the type of texture that should be used for a specific highway project. The proposed process will be particularly useful to highway agencies because its use will help identify textures that will provide adequate surface characteristics for concrete pavements.

Appendixes A through F contained in the research agency's final report provide detailed information on the literature review, test results, and data analysis, as well as a sample specification for texture. These appendixes are not published herein; but they are available on the TRB website. These appendixes are titled as follows:

Appendix A: State-of-the-Practice in Concrete Pavement Texturing
Appendix B: Report on Highway Agency and Industry Interviews
Appendix C: Existing Texture Test Sections
Appendix D: Texture, Friction, and Noise Results for Existing Test Sections
Appendix E: Texture, Friction, and Noise Results for Newly Constructed Test Sections
Appendix F: Sample Specifications for Texture

CONTENTS

1 Summary

5 **Chapter 1** Introduction
5 Background
5 Description of the Problem
6 Project Objectives and Scope
6 Work Approach
6 Overview of Report

7 **Chapter 2** State of the Practice
7 Literature Review
7 State and Industry Interviews
7 State-of-the-Practice Summary

14 **Chapter 3** Evaluation of Existing Texture Test Sections
14 Test Section Selection
14 Collection of Pavement Data
18 Test Section Descriptions
18 Texture, Friction, and Noise Testing of Existing Texture Test Sections
20 Agency-Supplied Friction Data
20 Texture, Friction, and Noise Test Results

27 **Chapter 4** Construction and Evaluation of New Test Sections
27 Selecting Surface Textures for Detailed Evaluation
27 Identification of a Candidate Paving Project
27 Project Overview
27 Construction of New Test Sections
30 Collection of Concrete Data
35 Texture, Friction, and Noise Test Procedures
38 Texture, Friction, and Noise Test Results

40 **Chapter 5** Data Analysis
41 Spectral Analyses
48 Comparative/Qualitative Analyses
72 Statistical Analyses
79 Texture Construction Analyses

81 **Chapter 6** Texture Selection Process
81 Texture Selection
90 Example Application of Texture Selection Process
90 Texture Construction Specifications and Practices

92 **Chapter 7** Conclusions and Recommendations for Future Research
92 Conclusions
93 Recommendations for Future Research
94 References
96 Abbreviations and Acronyms

AUTHOR ACKNOWLEDGMENTS

The research described herein was performed under NCHRP Project 10-67 by the Transportation Sector of Applied Research Associates (ARA), Inc. Dr. Jim W. Hall, Jr., was the Principal Investigator for the study.

Dr. Hall was supported in the research by ARA Research Engineers Mr. Kelly Smith, Mr. Paul Littleton, Dr. Shreenath Rao, and by former ARA Research Engineer Mr. Lynn Evans. Four project consultants—Dr. James Wambold (CDRM, Inc. and Professor Emeritus of Mechanical Engineering at Penn State University), Dr. David Kuemmel (D.A. Kuemmel Consulting Engineers and Adjunct Professor at Marquette University), Mr. John Jaeckel (HNTB Corporation), and Mr. David Wittwer (United Paving Contractors, Inc.)—also contributed significantly to the study.

The authors gratefully acknowledge those individuals from state departments of transportation (DOTs), industry organizations, and academia who participated in the interviews and/or provided important information and documentation for this project. The authors also express their gratitude to the Arizona, California, Colorado, Illinois, Iowa, Kansas, Michigan, Minnesota, Missouri, North Carolina, North Dakota, Texas, and Wisconsin DOTs for accommodating the data collection requests and the field testing on pavement test sections in their respective states.

Grateful recognition also goes to the Illinois Tollway for sponsoring the construction of texture test sections on the I-355 South Extension, as well as to the various entities who were actively involved in the construction of those sections, including H.W. Lochner, Inc. (construction consultant), K-Five Construction Co. (PCC paving contractor), Everest Engineering (quality assurance/quality control testing), and Quality Saw and Seal, Inc. (subcontractor, diamond grinding and grooving).

Finally, the team would like to acknowledge the following individuals and agencies who provided direct or indirect assistance in the testing of texture test sections:

- Dr. J.J. Henry—Provision of DF Tester and CT Meter equipment for testing of in-place test sections, and training in the use of the DF Tester and CT Meter, including data collection, troubleshooting, data transfer, and data analysis.
- Dr. Paul Donavan—Calibration testing of SI noise measuring system with Illingworth & Rodkin (I&R) SI system.
- Dr. Susanne Aref (Aref Consulting Group)—Statistical consulting and analyses using the SAS® statistical software.
- Mr. Curt Beckemeyer and Mr. Bill Vavrik (ARA, Inc.)—Soliciting and securing the participation of the Illinois Tollway in the texture construction demonstration.
- National Center for Asphalt Testing (NCAT)—DF Tester and CT Meter testing of both in-service and newly constructed test sections.
- International Cybernetics Corporation (ICC)—Provision, servicing, and calibration testing of ICC MDR 4081-T high-speed 64 kHz laser texture measurement system, and ASTM E 274 locked-wheel friction testing of new texture test sections.
- Dynatest Consulting, Inc.—ASTM E 274 locked-wheel friction testing of new texture test sections.
- Bruel & Kjaer—Training on the setup and use of the B&K PULSE analyzer and sound intensity (SI) measurement system, and the PULSE noise evaluation software and hardware.
- G.R.A.S. Sound and Vibration—Acoustical expertise and supply of phase-matched sound intensity microphones, free-field microphones, pre-amplifiers, and cables.
- Goodyear and Michelin Tire Companies—Supply of standard reference test tires.

SUMMARY

Texturing of Concrete Pavement

The objective of the research performed under NCHRP Project 10-67 was to recommend appropriate methods for texturing concrete pavements for specific applications and ranges of climatic, site, and traffic conditions. To accomplish this objective, several sequential tasks were performed.

First, information was collected, reviewed, and analyzed to establish the state of the practice in concrete pavement texturing and to identify innovative technologies. Next, a field investigation of pavement surfaces was conducted to identify concrete surface textures appropriate for construction and evaluation in a test site. The test site featured nine sections with "formed" textures (i.e., drag or tine finishes created in fresh concrete) and three sections with "cut" textures (i.e., ground or grooved finishes created in hardened concrete) that were tested for texture, friction, and noise shortly after construction.

Analysis of data obtained from both the in-place and newly constructed texture test sections was combined with information on the state of the practice to develop a process and guidelines for selecting textures for a range of applications and to prepare sample specifications for texturing concrete pavements.

Evaluation of Existing Test Sections

Several factors were considered in selecting texture test sections for evaluation in this research. The most important factors were (1) the availability of pavement sections with the desired textures, (2) the interest and willingness of state highway agencies (SHAs) to assist in evaluating the test sections, (3) the age of or amount of traffic experienced by the texture sections, and (4) the geographical locations and site conditions of test sections. Fifteen states were identified initially as having desirable test sections, and a testing matrix was developed—57 test sections in 13 states were selected for data collection and analysis. Design, construction, and site information for each of these test sections were obtained from state records. Also, various forms of texture, friction, and noise data for each section were available from field tests performed in 2005.

Construction and Evaluation of New Test Sections

Using a systematic procedure to rank the friction, texture, and noise characteristics of the existing test sections, the researchers identified several textures as having the potential to provide adequate friction and reduced noise characteristics. These textures were selected for additional evaluation through the construction of test sections as part of a paving project.

The Illinois State Toll Highway Authority (now the Illinois Tollway) provided an opportunity for constructing the texture test sections as part of a new alignment construction

project in the southwest suburbs of Chicago—the South Extension of the I-355 North-South Tollway located between I-55 and I-80 near Joliet. A total of 13 different textures, including 10 of the selected textures, were constructed in 2007 as part of the 6-lane, 12.5-mi (20.1-km) long project. Portland cement concrete (PCC) paving and formed texturing activities were closely monitored and documented, including measurements of groove dimensions (i.e., spacing and depth) at time of paving and at certain times after curing of the concrete. Also, the activities of three cut textures were closely monitored and documented.

Test segments for each texture were subsequently identified and marked in the field, with each segment chosen on the basis of best representation of the specified texture and avoidance of roadway features that could affect test results (e.g., overpasses, areas ground to satisfy smoothness requirements). These sections were tested for texture, friction, and noise in the same manner as was performed on the existing texture test sections.

Data Analysis

Different types of analyses were used to provide a basis for developing a practical, comprehensive process and guide specifications for texture type selection. The analyses recognized the limitations of the data and the role of micro- and macro-texture wavelengths on pavement friction and noise.

Noise spectral analyses of existing test sections showed prominent tonal spikes for three transverse tine textures with uniform spacing (one with 0.5-in. [12.7-mm] spacing and two with 0.75-in. [19-mm] spacing) and one longitudinal tine texture (0.75 in. [19 mm]). Two uniformly spaced (0.5 and 1 in. [12.7 and 25.4 mm]) transverse tine textures built on the Illinois Tollway exhibited similar tonal issues.

Power spectral density (PSD) analysis of texture profile data collected on the sections yielded additional texture properties (besides micro- and macro-texture and texture direction) for possible linkage to near-field sound intensity (SI) noise (i.e., noise at the pavement–tire source). These PSD parameters included two distinct ratios of high-frequency texture content to low-frequency texture content, and the peak texture wavelength. Plots of SI versus each of these PSD parameters generally confirmed that reducing the higher wavelength texture and increasing the lower wavelength texture results in lower noise.

Comparative/qualitative analyses of textures within a specific test site/location, followed by statistical analyses (analysis of variance [ANOVA] and statistical performance groupings), resulted in many observations regarding texture, friction, and noise performance. With respect to general texture types, it was concluded that longitudinal tining and longitudinal diamond grinding and grooving offer the greatest potential for reducing noise while maintaining adequate friction. Skewed variable transverse tine can eliminate objectionable tones and provide noise reduction benefits. Turf drag textures can be low noise, but significant texture depth is needed to ensure adequate friction at high speeds. With respect to the effect of texture orientation (TO) on noise, it was generally found that positive textures (i.e., aggressive, protruding surfaces) are noisier than negative textures (i.e., flat, pocketed surfaces). A key exception to this was diamond ground textures, which were categorized as positive textures, but exhibited low noise.

Texture durability analyses were performed to evaluate the effects of aggregate quality on micro-texture loss over time/traffic and macro-texture loss experienced by general texture types. This analysis showed that concrete mixtures with tougher, more durable aggregates retain higher friction values and that macro-texture loss over time/traffic is greatest for diamond-ground textures and lowest for dragged and grooved textures.

Time-/traffic-series noise comparisons of all concrete surface textures evaluated in the study showed diamond ground and grooved textures provided the lowest overall initial noise levels, followed by longitudinal drag, transverse tine, and longitudinal tine textures. Long-term overall noise was lowest for diamond-ground and grooved textures and longitudinal tining.

Various statistical analyses of the texture, friction, and noise data were conducted to distinguish the performance of the various textures and to identify the key factors affecting texture performance. These included SAS ANOVA and Tukey analyses of textures comprising individual sites/locations, SAS ANOVA and regression analyses of 70 test sections (57 existing sections and 13 newly constructed sections), and SAS multiple regression analyses/modeling of texture and noise from the newly constructed sections. Results of these analyses provided a basis for distinguishing and ranking different textures and for observing the effect of traffic on texture performance. These analyses also evaluated the influences of traffic, climate, and texture depth on friction/micro-texture performance and the influences of traffic, texture depth and direction, and joint frequency/spacing on pavement–tire noise. Other texture characteristics, such as texture orientation (TO) and certain texture power spectral density (PSD) parameters, and joint frequency/spacing on pavement–tire noise also were determined.

Texture Selection Process

Selecting a texture for a concrete pavement requires an understanding of the particular needs and requirements of the facility, and matching the friction and noise qualities of the available textures to those needs. A rational process is needed for determining the type of texture to be used on a particular highway project. Such a process involves gathering and reviewing all available critical information about the project, identifying potential constraints/limitations (both internally and externally) in terms of available resources/technologies and performance/cost expectations, developing alternative feasible solutions, and determining the most economical and practical alternative.

Figure S-1 illustrates the process for identifying pavement surface texturing options at the project level.

In this process, key information about the project is obtained and used to establish target levels for friction, noise, and other surface characteristics. The target levels are then combined with information on available aggregate types and contractor experience to generate feasible texturing options for the project. Once the options are identified, the cost of each texturing option (both initially and over the lifecycle of the pavement) is estimated, and the results are evaluated with consideration given to the overall functional and structural requirements and performance of the pavement.

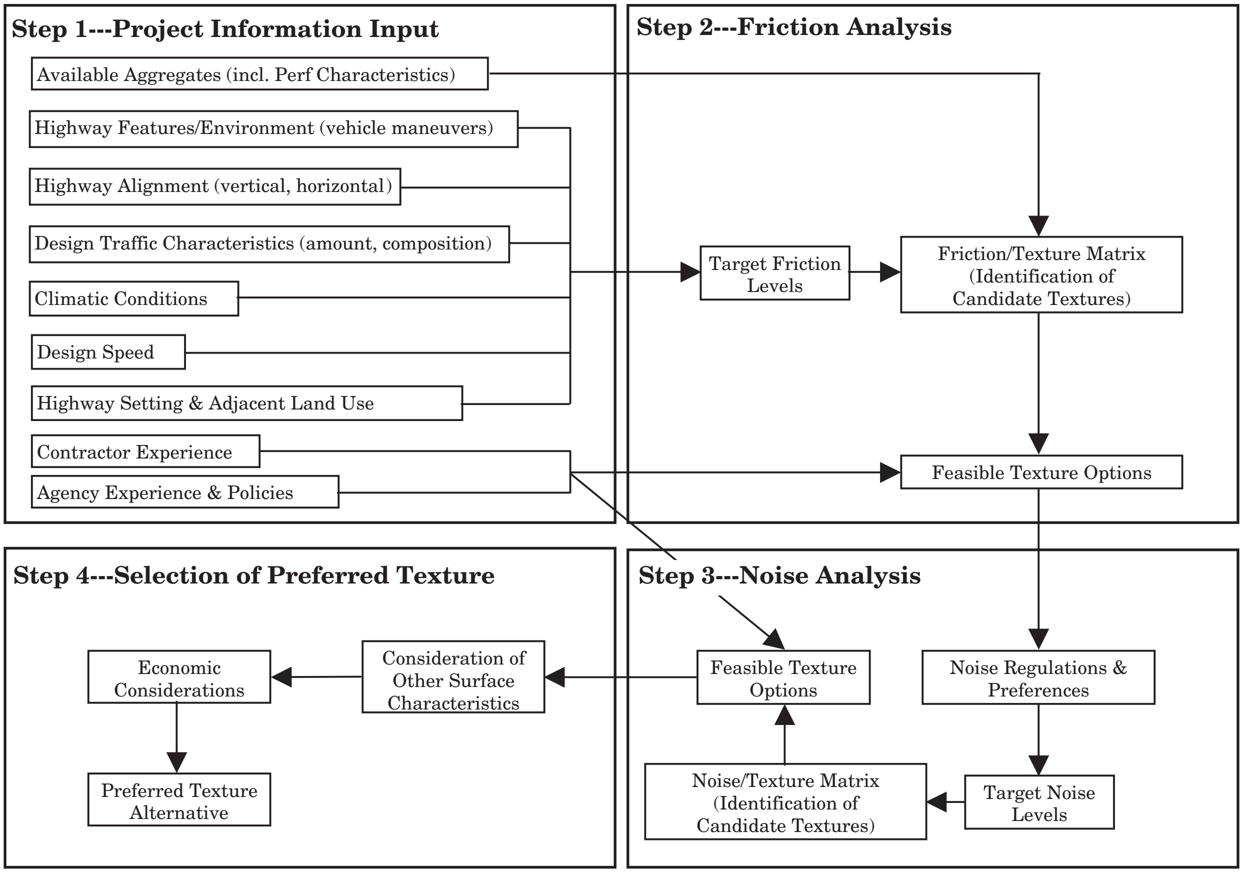


Figure S-1. Process for identifying pavement surface texturing options.

CHAPTER 1

Introduction

Background

It has long been recognized that the texture of portland cement concrete (PCC) pavement surfaces directly influences friction and safety characteristics (American Concrete Institute [ACI], 1988). Prior to 1967, most PCC surface textures were constructed using a burlap drag process. However, at that time, this texturing method did not provide a minimum frictional coefficient of 0.30, as was required by at least one state—California (Neal, 1985). Consequently, other texturing methods were developed to improve frictional/safety characteristics, the most common of which is transverse tining (grooving the PCC surface perpendicular to the traffic direction prior to curing). The uniform narrow grooves provide water drainage and increase the macro-texture of the surface, resulting in good wet-weather pavement–tire friction and reportedly a good safety record.

As the volume of urban traffic increased steadily, vehicle noise emission became a concern (ACI, 1988). In 1973, the Federal Highway Administration issued *Policy and Procedure Memorandum 90-2, Noise Standards and Procedures* that established noise criteria for federally funded highway projects (FHWA, 1973). From this time through 2004, over 2,205 mi (3,550 km) of noise barriers or combination berms and barriers were built at a cost of over $2.7 billion (FHWA, 2006). The criteria have since been updated and are currently outlined in the *Code of Federal Regulation (CFR) Title 23, Part 772, Procedures for Abatement of Highway Traffic Noise and Construction Noise* (U.S. Federal Government, 2008).

While significant reductions in vehicle engine and drive-train noises were achieved in recent years, the noise associated with pavement–tire interaction has not been significantly reduced (Sandberg and Ejsmont, 2002). Public concern (especially in urban areas) over the issue of high traffic noise and the substantial costs associated with noise emissions barriers have led to renewed interest in pavements that exhibit low-noise properties under traffic.

Because pavement–tire noise is controlled primarily by (1) the tire design and materials and (2) roadway surface texture and material properties, the highway community has been actively engaged in evaluating the methods used to texture pavements. Spurred on by the significantly lower noise of asphalt concrete (AC) pavement surfaces when compared with transversely tined PCC surfaces, particular effort has been devoted to developing improved alternatives to the transverse tine texture. Among the earlier alternatives were (1) the longitudinal tine that California specified starting in 1978 in spite of the requirement of FHWA guidelines for transverse tining (Neal et al., 1978; Hibbs & Larson, 1996); (2) the random (i.e., variable) transverse tine that was found to reduce or eliminate the "whine" associated with uniform transverse tining; and (3) the random (i.e., variable) skewed transverse tine that was shown to eliminate whine and reduce overall noise (Kuemmel et al., 2000).

Other methods of noise reduction for PCC pavements have been evaluated internationally and more recently in the United States. These include longitudinal diamond grinding, longitudinal grooving, exposed aggregate concrete (EAC), porous PCC, shot-abraded PCC (e.g., Skidabrader), and ultra-thin proprietary surfacings (e.g., NovaChip® and Italgrip® System). Various strengths and weakness have been reported for all of the methods with regard to initial and long-term noise, friction, and other surface characteristics, as well as constructability and economics. Identifying optimal textures for various highway conditions and environments has been the goal in many of the past and ongoing investigations, and it is the goal in this study.

Description of the Problem

Tining generally is performed to enhance pavement-surface frictional characteristics and reduce potential for hydroplaning, skidding, and wet-weather crashes. However, there is a concern that the use of tining has evolved without adequate consideration of the effects on noise generation, long-term durability, smoothness, constructability, pavement serviceability, and cost-effectiveness. In addition, there are other options for texturing concrete pavements that might provide better performance and yield environmental and economic benefits.

There are no widely accepted guidelines or procedures for identifying and selecting methods of texturing concrete pavements that consider relevant technical, environmental, economic, and safety issues. Research was needed to develop a rational procedure for use by highway agency personnel in identifying and selecting appropriate texturing methods for concrete pavements. NCHRP Project 10-67 was initiated to address this need.

Project Objectives and Scope

The objective of this research was to recommend appropriate methods for texturing concrete pavements for specific applications and ranges of climatic, site, and traffic conditions. These methods were to include tining and other means of texturing fresh and hardened concrete for the purpose of enhancing surface frictional characteristics.

The research included a review of relevant literature, conducting surveys and interviews of state and industry professionals, identifying and assessing the factors that influence texture level, and identifying test methods and criteria for assessing surface texturing. The research also included a field evaluation of in-place test sections and specially constructed full-scale test sections. Based on the analysis of acquired data, a process for texture selection and sample construction specifications were prepared.

Work Approach

In this study, a large amount of information was collected, reviewed, and analyzed to establish the state of the practice in concrete pavement texturing and to identify promising and/or innovative texturing methods. A large field investigation involving texture, friction, and noise testing of 57 in-place pavement surfaces was conducted.

Results from this investigation were used to identify concrete surface textures for a more detailed evaluation through the construction of a formal texture test site. This test site, located and installed on a new stretch of the I-355 North-South Tollway near Joliet, Illinois, included nine different "formed" textures (tining or drag finishes created in fresh concrete) and three different "cut" textures (ground or grooved finishes created in hardened concrete), all of which were tested for texture, friction, and noise shortly after construction.

The results of data analyses on both the in-place and new texture test sections together with the state of the practice information were used to develop a process (and related guidance) for selecting textures for a range of applications and for preparing sample specifications for texturing concrete pavements.

Overview of Report

This report has seven chapters. Chapter 1 is this introduction. Chapter 2 briefly describes the state of the practice of concrete pavement surface texturing based on a review of literature and interviews with knowledgeable individuals. Chapter 3 describes the selection of 57 pavement sections located in 13 states and the conduct of texture, friction, and noise tests. Chapter 4 discusses the development and execution of a plan to build and test different surface textures (most of them identified as having good friction and noise qualities) as part of a paving project in northern Illinois.

Chapter 5 presents the results of analyses performed on texture, friction, noise and other pavement data collected on both existing and newly constructed test sections. The results together with the state-of-the-practice information were used to develop the texture selection process presented in Chapter 6. The final chapter summarizes the key findings of this research and presents the study's conclusions and recommendations.

The report includes six appendices. Appendix A describes the state of the practice in concrete pavement texturing. Appendix B summarizes the interviews conducted with highway agency, industry, and academia representatives. Appendix C gives detailed information on the locations, layout, and history of the 57 existing test sections. Appendixes D and E provide summary charts of the texture, friction, and noise testing results obtained for existing and newly constructed texture test sections, respectively. Appendix F presents guide/sample specifications for some of the PCC textures evaluated in this study. Appendixes A through F are not published herein, but are available on the TRB website.

CHAPTER 2

State of the Practice

This chapter summarizes the state of the practice with regard to concrete pavement surface texturing, as gleaned from the literature reviews and interviews with experienced and knowledgeable individuals. The summary of current practices deals with the following items:

- Surface properties most relevant to the selection of a texture type.
- Methods used to measure or test the relevant surface properties.
- Types of textures available for use.
- Properties typically exhibited or possessed by individual texture types.

Literature Review

A literature search focused on information pertaining to concrete pavement texture, friction, noise, and other related surface characteristics was conducted. This search involved domestic and international sources available from public agencies, industry, academic institutions, and other organizations.

Pertinent documents were reviewed (a synthesis of this information is provided in Appendix A which is available online). Key aspects of the synthesis are included in the state-of-the-practice summary presented in this chapter.

State and Industry Interviews

The literature search effort was supplemented with interviews with several state highway agency (SHA) and industry representatives, and experts in the area of pavement surface characteristics. The interviews sought (1) information on SHA policies, practices, experiences (including past studies), and perspectives on pavement frictional properties, texture, and noise; and (2) insights and information from other public or private institutions engaged in these issues. Information was sought about in-service pavements suitable for inclusion in the field evaluations.

Individuals from 18 highway agencies, 15 industry groups, and 13 international and related sources were interviewed. Interviewees included representatives of texture, friction, and noise measuring equipment manufacturers/vendors; noise testing facilities; friction and profile testing calibration centers; paving contractor agencies; construction materials and equipment manufacturers, and tire manufacturers.

The information obtained from the state and industry interviews was synthesized and is provided in Appendix B. Key aspects of this synthesis are included in the state-of-the-practice summary provided in this chapter.

State-of-the-Practice Summary

Pavement Surface Properties

Pavement surface texture is made up of the deviations of the pavement surface from a true planar surface. These deviations occur at three distinct levels of scale, each of which is defined by the wavelength (λ) and peak-to-peak amplitude (A) of its components. The three levels of texture, as established by the Permanent International Association of Road Congresses (PIARC) (1987), are as follows:

- Micro-texture ($\lambda < 0.02$ in. [0.5 mm], $A = 0.04$ to 20 mils [1 to 500 μm])—Surface roughness quality at the sub-visible/microscopic level. It is a function of the surface properties of the aggregate particles within the asphalt or concrete paving material.
- Macro-texture (0.02 in. $\leq \lambda < 2$ in. [0.5 mm $\leq \lambda <$ 50 mm], $A = 0.005$ to 0.8 in. [0.1 to 20 mm])—Surface roughness quality defined by the mixture properties (shape, size, and gradation of aggregate) of an asphalt paving material and the method of finishing/texturing (dragging, tining, grooving; depth, width, spacing and direction of channels/grooves) used on a concrete paving material.
- Mega-texture (2 in. $\leq \lambda < 20$ in. [50 mm $\leq \lambda <$ 500 mm], $A = 0.005$ to 2 in. [0.1 to 50 mm])—This type of texture is

the texture which has wavelengths in the same order of size as the pavement–tire interface. It is largely defined by the distress, defects, or "waviness" on the pavement surface.

Pavement surface texture influences many different pavement–tire interactions. Figure 2-1 shows the ranges of texture wavelengths affecting various vehicle–road interactions, including friction, interior and exterior noise, splash and spray, rolling resistance, and tire wear. As can be seen, micro-texture contributes significantly to surface friction on dry roads at all speeds and on wet roads at slower speeds, while macro-texture significantly influences surface friction on wet road surfaces with vehicles moving at higher speeds. Highway noise is affected by the macro-texture and mega-texture of a roadway, while splash/spray is affected primarily by macro-texture.

Methods of Measuring Pavement Surface Properties

Several types of equipment and procedures have been developed and used over the years to measure pavement surface properties. Current standardized or widely accepted testing methods for measuring texture, friction, and noise include:

- Texture
  - Sand Patch Method (SPM) (ASTM E 965)
  - Outflow Meter (OF Meter) (ASTM E 2380)
  - Circular Texture Meter (CT Meter) (ASTM E 2157)
  - High-speed Laser Profiler (ASTM E 1845)
- Friction
  - Locked-wheel Friction Tester (ASTM E 274)
  - Dynamic Friction Tester (DF Tester) (ASTM E 1911)
  - British Pendulum Tester (BPT) (ASTM E 303)
- Noise
  - Controlled pass-by (CPB) method (NF S 31 119-2) [ISO 5725)
  - Statistical pass-by (SPB) method (ISO 11819-1)
  - Close-proximity (CPX) method (ISO/DIS 11819-2)
  - Coast-by (CB) method (ISO/DIS 13325 and Directive 2001/43/EC)
  - Trailer coast-by (TCB) method (ISO/DIS 13325)
  - Acceleration pass-by (APB) method (ISO 362)
  - Sound intensity (SI)/On-Board Sound Intensity (OBSI) method (General Motors [GM] standard and AASHTO Provisional Standard TP076-08)
  - Interior vehicle method (Society of Automotive Engineers [SAE] J 1477)

Brief descriptions and assessments of these methods are provided in this chapter; more details are provided in Appendix A.

Texture Measurement

The SPM method, the OF Meter, and the CT Meter are texture measuring equipment requiring lane closures. Also, a recently developed line laser system named RoboTex (Robotic Texture), which gives three-dimensional texture readings, requires lane closure.

The SPM (ASTM E 965) is a volumetric-based spot test method that assesses pavement surface macro-texture through

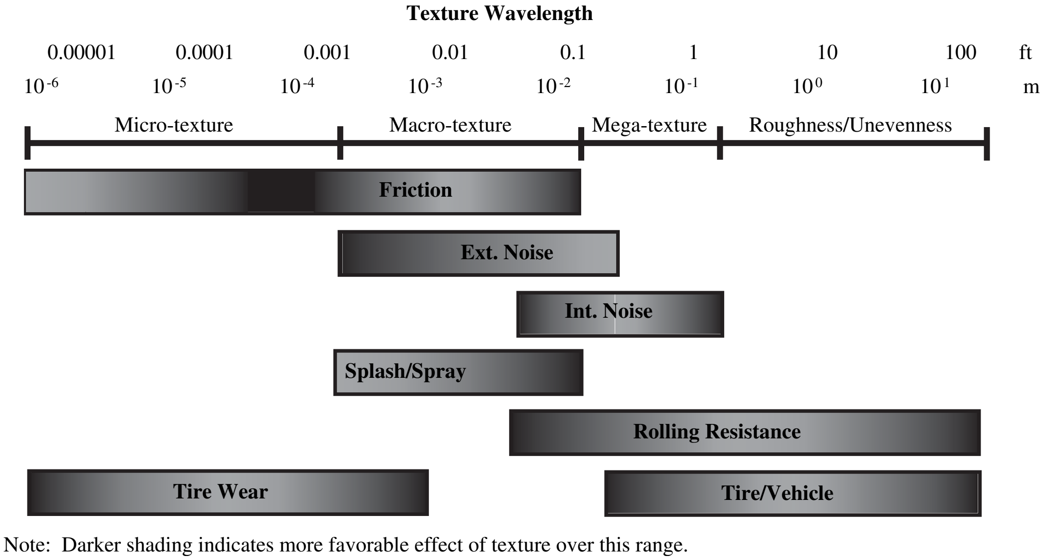


Figure 2-1. Texture wavelength influence on pavement–tire interactions (adapted from Henry, 2000 and Sandberg and Ejsmont, 2002).

the spreading of a known volume of glass beads in a circle onto a cleaned surface and the measurement of the diameter of the resulting circle. The volume divided by the area of the circle is reported as the mean texture depth (MTD).

The OF Meter (ASTM E 2380) is a volumetric test method that measures the water drainage rate through surface texture and interior voids. It relates the hydroplaning potential of a surface to the escape time of water beneath a moving tire. The equipment consists of a cylinder with a rubber ring on the bottom and an open top. Sensors measure the time required for a known volume of water to pass under the seal or into the pavement. The measurement parameter, outflow time (OFT), defines the macro-texture; high OFTs indicate smooth macro-texture and low OFTs rough macro-texture.

The CT Meter (ASTM E 2157) is a non-contact laser device that measures the surface profile along an 11.25-in. (286-mm) diameter circular path of the pavement surface at intervals of 0.034 in. (0.868 mm). The texture meter device rotates at 20 ft/min (6 m/min) and generates profile traces of the pavement surface, which are transmitted and stored on a portable computer. Two different macro-texture indices can be computed from these profiles—mean profile depth (MPD) and the root mean square deviation of the profile (RMS). The MPD, which is a two-dimensional estimate of the three-dimensional MTD (ASTM 2157), represents the average of the highest profile peaks occurring within eight individual segments constituting the circle of measurement. The RMS is a statistical value, which offers a measure of how much the actual data (measured profile) deviates from a best-fit (modeled profile) of the data (Abe et al., 2000).

High-speed methods for characterizing pavement surface texture typically are based on non-contact surface profiling techniques. An example of a non-contact profiler for use in characterizing pavement surface texture is the Road Surface Analyzer (ROSAN$_V$), developed by the FHWA. ROSAN$_V$ is a portable, vehicle-mounted, automated system for measuring pavement texture at highway speeds along a linear path (FHWA, 2008). ROSAN$_V$ incorporates a laser sensor mounted on the vehicle's front bumper and the device can be operated at speeds of up to 70 mi/hr (113 km/hr). The system calculates both MPD and estimated mean texture depth (EMTD), which is an estimate of MTD derived from MPD using a transformation equation. Automated profile measurement systems such as ROSAN$_V$ provide a large quantity of texture data and enhance safety by eliminating the traffic control required for manually performed volumetric methods.

Friction Testing

The most common method for measuring pavement friction in the United States is the ASTM E 274 using locked-wheel testing equipment supplied with either a ribbed (ASTM E 501) or smooth (ASTM E 524) test tire. This method, used for routine network surveys and/or project-level testing, uses a friction index called the Friction Number (FN) to quantify the level of available friction under wetted conditions. The speed at which the test is performed (typically 40 mi/hr [64 km/hr]) and the type of test tire used (ribbed or smooth) further delineate the friction parameter (i.e., FN40R or FN40S represent friction values obtained at 40 mi/hr [64 km/hr] with ribbed or smooth tires, respectively).

Friction measurement using a ribbed test tire does not adequately assess road macro-texture, because tire grooves allow for removal of water at the pavement–tire interface, eliminating the need for good road macro-texture (Henry, 2000). Recent studies (PIARC, 1995) suggest the addition of lasers to measure macro-texture, and most new testers are now being ordered with texture lasers. This allows for measurements at speeds other than the standard 40 mi/hr (64 km/hr), with a way to adjust the measurement to 40 mi/hr (64 km/hr). Thus, measurements can be done at higher speeds on interstates and lower speeds in towns and at intersections, and then adjusted to a common speed of 40 mi/hr (64 km/hr).

The DF Tester (ASTM E1911) allows measuring friction (expressed as DFT) as a function of speed over the range of 0 to 56 mi/hr (0 to 90 km/hr) (Flintsch et al., 2003). The DFT friction parameter is accompanied by the speed at which the test is performed; hence, the typical speed of 12.5 mi/hr (20 km/hr) is designated as DFT12.5 or, more commonly, DFT(20). DFT(20) has been found to correlate well with BPN and is generally used as the reporting friction value (Henry, 2000).

Noise Evaluation

As described by Bernhard and Wayson (2005), noise is defined as unwanted sound and is typically expressed in terms of sound pressure level (SPL). The formula for SPL, which uses a logarithmic scale and is reported in decibels (dB), is as follows:

$$\mathrm{SPL} = 10 \times \log_{10}\left(p^2/p_{ref}^2\right) \qquad \text{Eq. 2-1}$$

where

p = Sound pressure of concern, Pa

p_{ref} = Standard reference pressure $= 20 \times 10^{-6}$ Pa

SPL adjusted to the sensitivity of human hearing (i.e., attenuation of low [<500 Hz] and high [>5,000 Hz] frequencies) is referred to as A-weighted sound (Bernhard and Wayson, 2005). The unit of measure is the A-weighted decibel or dB(A).

The primary method for detailed evaluation of highway noise in the United States (and most of Europe) is the SPB method, which measures the maximum sound level (L_{max}) for a mix of vehicles. The measurement is taken from the side of the road at a specified distance from the center of the travel lane (typically, 50 ft [15 m] in the United States and 25 ft [7.5 m] in Europe) and at a specified height above the travel surface (5 ft [1.5 m] in the United States and 4 ft [1.2 m] in Europe). The SPB method provides noise values that are representative of a wide range of vehicles; however, it is somewhat costly and time-consuming and results in considerable variability with different vehicles using different roads.

A similar method, the CPB method, offers the ability to compare roadside noise (L_{max}) of different road sections directly using specific vehicle properties and speeds. Although a little less time-consuming than SPB, this method only provides the ability to compare the roadside noise properties from the vehicle(s) used in the evaluation; CPB may not well represent the overall roadside noise experienced by the neighboring community. CPB was used in a study completed in 1999 (Kuemmel et al., 2000), because it provided direct comparison of roadside noise of road surfaces.

The two most common methods of measuring near-field pavement–tire noise (i.e., noise at or very near the source) are the CPX and SI methods. The CPX method, which uses sound pressure microphones to measure average dB(A) at 0.3 to 1.6 ft (0.1 to 0.5 m) from a reference tire in an enclosed, sound-absorbing trailer, is relatively inexpensive, fast, and can be used to continuously document the noise characteristics (including variability) of long portions of highway. It has been used in Europe for many years, and a modified CPX noise trailer was used in recent years to evaluate noise on pavement sections in several states (Scofield, 2003; Hanson and James, 2004; Hanson, 2002). Correlations between sound pressure CPX values and roadside CPB levels have been noted as inconsistent (Chalupnik, 1996).

The SI method was originally developed by GM and has been used in the United States since the 1990s for conducting pavement–tire noise evaluations. It uses microphones mounted next to the tire of the test vehicle and measures the rate of energy flow through a unit area, which when integrated over the area provides sound pressure. Because these microphone pairs are directional, they are not significantly affected by adjacent tire and wind noise. *NCHRP Report 630* (Donavan and Lodico, 2008) contains the SI test procedure that provided a basis for the AASHTO Provisional Standard TP076 for measurement of tire–pavement noise using the OBSI method (AASHTO TP076, 2008).

Interior vehicle noise measurement entails the continuous measurement of noise inside the test vehicle as it travels along a road at a specified speed. The measurement location is at a point 2.25 ft (0.7 m) above the front passenger seat. The collected noise data for a given run are used to compute the equivalent sound pressure level (L_{eq}), which is obtained by adding up all the sound energy during the measurement period and then dividing it by the measurement time (Rasmussen et al., 2007a). Interior vehicle noise is generally a much lower frequency than exterior noise, because the vehicle not only attenuates the high frequency noise, but amplifies the low frequency noise (Rasmussen et al., 2007a).

Texturing Methods for Concrete Pavements

The following methods are used in the United States and other countries for texturing new concrete pavements or retexturing existing concrete pavements:

- Plastic brushing/brooming
- Transverse and longitudinal dragging
- Transverse and longitudinal tining
- Transverse and longitudinal grooving
- Longitudinal diamond grinding
- Exposed Aggregate Concrete (EAC) surfacing
- Porous concrete
- Shot abrading

In addition, in lieu of retexturing, other options have been used for enhancing the surface characteristics of concrete pavements, such as thin (≤1.5 in. [38 mm]) asphalt overlays, ultra-thin (0.375 to 0.75 in. [9.5 to 19.0 mm]) bonded wearing courses (i.e., NovaChip® proprietary treatment), and ultra-thin (0.12 to 0.25 in. [3.0 to 6.0 mm]) epoxied laminates (i.e., Italgrip® System proprietary treatment).

FHWA *Technical Advisory T5040.36* (Surface Texture for Asphalt and Concrete Pavements) (2005) contains recommendations for the applications of many of these textures. A summary of the properties and performance characteristics of the above textures and their relative desirable rankings is provided below. Descriptions of the strengths and weaknesses of each method are given in Appendix A.

Texture Properties and Performance Characteristics

Each of the identified methods has properties and performance characteristics that make them more or less desirable for different paving applications. Table 2-1 summarizes the ranges of initial texture, friction, and noise properties reported for each method in the United States. Some examples of the texture depth produced as a result of different tine dimensions are provided in Table 2-2, based on measurements made on various in-service pavement sections (Kuemmel et al., 2000). Table 2-3 summarizes the strengths, weaknesses, and typical costs for each method based on the information available in the literature (Wittwer, 2004; Chandler et al., 2003; Billiard, 2004; Beeldens et al., 2004; Exline, 2004; APTech, 2001).

Tentative Benefit Rankings

Selecting the appropriate methods for PCC texturing in different applications requires a balance of maintaining adequate

Table 2-1. Texture, friction, and noise ranges.

Method	Texture Range		Friction Range		Noise Range	
	MTD, mm	MPD, mm	FN40R	FN40S	CPX, dB(A)	CPB L_{max}, dB(A)
Transverse tine (0.75 in.)	0.53 to 1.1	0.50 to 0.52	41.0 to 56.0	30.6 to 34.4	100.4 to 104.8	83.0 to 84.0
Transverse tine (0.5 in.)		0.35 to 1.00	54.0 to 71.0	37.6 to 62.0		81.9 to 83.0
Transverse tine (variable)	1.14	0.42 to 1.02		50.0 to 69.5		81.0 to 87.3
Transverse groove	1.07			48.0 to 58.0		84.1 to 84.6
Transverse drag	0.76		22.0 to 46.0			
Longitudinal tine	1.22			36.0 to 76.6	96.6 to 103.5	79.0 to 85.0
Longitudinal groove	1.14			48.0 to 55.0	99.4 to 103.8	80.9
Longitudinal grind	0.30 to 1.20		35.0 to 51.0	29.9 to 46.8	95.5 to 102.5	81.2
Longitudinal burlap drag					101.4 to 101.5	
Longitudinal turf drag	0.53 to 1.00		23.0 to 55.6	20.0 to 38.0	97.4 to 98.6	83.7
Longitudinal plastic brush			48.0 to 52.0	23.0 to 24.0	101.8 to 102.2	
EAC	0.9 to 1.1		35.0 to 42.0			
Shot abraded PCC	1.2 to 2.0			34.3 to 46.2		84.3
Porous PCC						
Ultra-thin epoxied laminate	1.4					79.8
Ultra-thin bonded wearing course	0.97 to 1.98		26.0 to 27.0		95.0 to 99.0	

1 in. = 25.4 mm

short- and long-term wet-weather friction levels, minimizing pavement–tire noise, maintaining road durability, and minimizing construction and maintenance costs. The information gathered and analyzed provided a sufficient basis for developing tentative rankings according to these categories. The texture method benefit rankings shown in Table 2-4 were determined based on a subjective assessment of the available information.

Each paving project includes specific demands for levels of friction, noise, cost, and constructability. Low-speed rural or industrial projects in a dry climate with no curves and intersections will demand less noise reduction and less friction than an urban, high-speed throughway that includes several curves and intersections and bisects a residential community. Cost restrictions for the latter may also be less stringent. Aggregate costs may also affect the texturing option chosen. Therefore, the individual category rankings will need to be considered in selecting the optimum texturing methods for each project. It is unlikely that one surface texturing method will always be the best choice in any highway agency (FHWA, 1996a).

Highway Agency Texturing Policies and Practices

The highway agencies interviewed in this study reported various policies and practices regarding texturing of new concrete pavements. The texturing methods for high-speed (>40 to 45 mi/hr [64 to 72 km/hr]) pavements are summarized in Table 2-5. Although responses were provided by only 16 states, the general indication is that transverse tining using various patterns and dimensions is currently the most common form of texturing; only a few agencies use longitudinal tining. Several European agencies use one- or two-layer EAC surfaces for new concrete construction. (Additional information on highway agency texturing policies and practices is provided in Appendix B which is available online.)

Table 2-2. Texture depths observed for different groove spacings and depths.

Texture Type	Design Groove Spacing, in.	Avg. Groove Depth, mm	Avg. Texture Depth (MPD)	No. Sections Tested/Evaluated
Transverse Tine, Uniform Spacing	0.5	1.4	0.54	5
	0.75	1.7	0.51	2
	1.00	1.9	0.46	5
Transverse Tine, Variable Spacing	0.75	2.1	0.64	5
	1.00	2.2	0.54	2
	1.50	1.9	0.38	2
Longitudinal Tine	0.75	2.2	0.82	3
	1.00	–	0.62	2

1 in. = 25.4 mm

Table 2-3. Constructability, design, and cost comparison for various surface textures.

Method	Strengths	Weaknesses	Initial Cost[1], \$/yd^2
Longitudinal burlap drag	Automated, simple construction Good noise properties	Moderate initial friction and early friction loss	0.10 to 0.15
Longitudinal turf drag	Lower noise, high friction Simple construction and early cure application	Long-term friction not well defined Aggregate and mortar strength are critical	0.10 to 0.15
Longitudinal plastic brush/broom	Automated or manual application Good noise properties	May not maintain texture, friction, and safety properties	0.10 to 0.15
Transverse drag	Small positive surface water drainage flow	Slow and expensive operation	N/A
Transverse tine (0.75 in.)	Durable high friction Automated or manual construction	Very high noise and tonal whine Variable depending on weather and operator No positive surface drainage when longitudinal slope is less than cross-slope	0.10 to 0.15
Transverse tine (0.5 in.)	Durable high friction Automated or manual construction	High noise and some tonal whine Variable depending on weather and operator No positive surface drainage when longitudinal slope is less than cross-slope	0.10 to 0.15
Transverse tine (variable)	Durable high friction, automated or manual No tonal whine if properly designed/constructed	High noise Variable depending on weather and operator No positive surface drainage when longitudinal slope is less than cross-slope	0.10 to 0.15
Transverse tine (skewed variable)	Durable high friction, automated or manual No tonal whine if properly designed/constructed	High noise Additional effort required to construct No positive surface drainage when longitudinal slope is less than cross-slope	0.10 to 0.15 (unless joints avoided)
Longitudinal tine	High friction, lower noise and no tonal whine Automated construction required	Some annoyance or perceived handling problems may be experienced by motorcyclists or drivers of light vehicles, however safety not impacted No positive surface drainage channels	0.10 to 0.15
Longitudinal groove	Provides retrofit macro-texture to old roads Minimal traffic interruption or worker exposure	Some annoyance or perceived handling problems may be experienced by motorcyclists or drivers of light vehicles, however safety not impacted No positive surface drainage channels	1.25 to 3.00
Longitudinal grind	High friction, low noise, low worker exposure Increased smoothness	Friction decreases rapidly on polish susceptible coarse aggregate with heavy traffic.	1.00 to 5.45
Transverse groove	Provides retrofit macro-texture to old roads Minimal traffic interruption or worker exposure	Slow and expensive operation	4.00 to 8.20
EAC	Good noise and friction properties Long-term noise and friction stable	Special equipment and methods are required Contractor experience is critical to performance	2.50 to 5.00
Shotblasted PCC	Provides retrofit macro-texture to old roads Minimal traffic interruption or worker exposure	Limited improvement in noise properties	1.50 to 2.00
Porous PCC	Very good noise, high friction, low splash/spray	Mostly experimental designs Noise reduction reduces with void filling	10.00 to 11.35
Thin HMA Overlay[2] (1.0 to 1.5 in.)	Very good noise properties Generally good friction	Vertical clearance decreased Splash/spray an issue, particularly for finer mixes	2.50 to 4.50
Ultra-thin epoxied laminate	Good friction No clearance issues	Extremely expensive	16.50 to 20.00
Ultra-thin bonded wearing course	Good noise, high friction, low splash/spray Fast application, improved smoothness	Vertical clearance slightly decreased	2.50 to 5.00

[1] For concrete textures, unit costs represent only the cost of the texturing activity (or in the case of porous PCC, the added cost of producing and placing a porous mixture). For the three asphalt textures, the unit costs are representative of the specific material and its placement.

[2] Assumes existing pavement is in generally good condition and needs minimal pre-overlay repairs.

1 in. = 25.4 mm

1 yd^2 = 0.84 m^2

Table 2-4. Tentative texture method benefit rankings.

Method	Friction	Exterior Noise	Cost	Constructability
Transverse tine (0.75-in spacing)	1	8	1	2
Transverse tine (0.5-in. spacing)	1	6	1	2
Transverse tine (variable spacing)	1	7	1	2
Transverse groove	1	7	4	3
Transverse drag	2	6	–	2
Longitudinal tine	1	4	1	1
Longitudinal groove	1	5	3	3
Longitudinal grind	1	3	3	3
Longitudinal burlap drag	4	3	1	1
Longitudinal turf drag	2	3	1	1
Longitudinal plastic brush	3	3	1	1
EAC	2	3	3	4
Shotblasted PCC	1	7	2	3
Porous PCC	1	1	5	4
Ultra-thin epoxied laminate	1	2	6	3
Ultra-thin bonded wearing course	2	2	3	3

1 = Best/highest ranking

Table 2-5. Highway agency texturing practices for new concrete pavements.

Highway Agency		Texturing Method	Optional Texturing Methods
States	Alabama	Tran Tine (13 to 25 mm variable) w/ Burlap Drag	
	California	Long Tine (19 mm) w/ Burlap Drag	Burlap Drag (mountains), Long Groove
	Colorado	Long Tine (19 mm)	
	Florida	Tran Tine (13 to 25 mm variable) w/ Burlap Drag	
	Illinois	Tran Tine (19 mm) w/ Long Turf Drag	Tran Tine (17 to 54 mm variable) w/ Long Turf Drag
	Indiana	Tran Tine (variable) w/ Long Turf Drag or Burlap Drag	
	Iowa	Tran Tine (19 mm) w/ Long Turf Drag or Burlap Drag	Long Tine (19 mm), Tran Tine (9.5 to 41 mm)
	Kansas	Long Tine (19 mm) w/ Burlap Drag or Long Turf Drag	
	Michigan	Tran Tine (13 mm slightly variable)	
	Minnesota	Long Turf Drag (≥ 1 mm MTD)	
	Missouri	Any method (≥ 0.7 mm MTD)	Tran Tine (13 mm), Long Tine (13 mm), Long Grind
	North Carolina	Tran Tine (13 to 19 mm variable) w/ Burlap Drag	
	North Dakota	Tran Tine (13 to 71 mm variable) w/ Long Turf Drag	
	Pennsylvania	Tran Tine (15 to 54 mm variable)	
	Texas	Tran Tine (25 mm) w/ Long Turf Drag	
	Wisconsin	Tran Tine (15 to 54 mm variable) w/ Long Turf Drag	
Countries	Austria	EAC (2 layer)	
	Belgium	EAC (1 layer)	Long Tine, Long Grind
	Germany	Burlap Drag (MTD 0.4 to 0.6 mm)	
	Japan	Long Groove	
	Netherlands	EAC (1 layer)	
	Spain	Long Tine-Sinusoid (25 to 30 mm) (MTD 0.6 to 0.9 mm)	
	Sweden	EAC	Long Grind
	United Kingdom	EAC	

1 in. = 25.4 mm

CHAPTER 3

Evaluation of Existing Texture Test Sections

This chapter describes the process of selecting and conducting texture, friction, and noise testing on several existing pavement sections located throughout the United States. This effort took place in the spring, summer, and fall of 2005 (some minor follow-up work was done in summer 2006) and resulted in the collection of detailed surface characteristics data on these test sections.

This chapter also describes (1) the selected test sections, (2) the collection of historical pavement data (e.g., design, materials, construction, and performance/condition) and site/conditions data (e.g., climate, traffic, geometrics, speed), and (3) the testing protocols used for field measurements. This chapter also summarizes the results of the testing.

Test Section Selection

Various factors were considered in selecting test sections for evaluation. The most important factors were (1) the availability of pavement sections with the desired textures, (2) the interest and willingness of SHAs to assist in evaluating the test sections (e.g., coordinating traffic control, conducting friction testing, and providing pavement and other relevant data on the test sections), (3) the age of or amount of traffic accumulated on the test sections, and (4) the geographical locations and site conditions. The last factor was used to select sections representative of different climatic and traffic conditions, as well as the texturing application (i.e., texturing of new pavement versus retexturing of existing pavement).

Initially, Arizona, California, Colorado, Florida, Georgia, Iowa, Kansas, Michigan, Minnesota, Missouri, North Dakota, Pennsylvania, Texas, Virginia, Washington, and Wisconsin were identified as having desirable test sections (i.e., promising textures) and were considered for inclusion in the study. NASA Wallops was also considered because various textures were previously installed at the site. Sections in some of these locations, including NASA Wallops, were removed from consideration once it was determined that other sections were better candidates.

An initial list of potential test sections in these locations was identified and later updated to include additional desirable test sections identified through discussions with state DOTs (Table 3-1). This list does not include several alternate sections identified as potential backups to the first two options. Also, while most of the sections represent relatively new, lightly trafficked pavements, five of these sections represent older, more heavily trafficked pavements (shaded cells). These more-trafficked sections were included to evaluate the effects of traffic.

In the weeks leading up to and during the course of field testing, various changes were made to the tentative list. For instance, testing on some sections (e.g., Georgia, Texas, and Quebec) could not be completed due to problems with the testing equipment or time constraints. Other changes were made to exclude sections with inadequate pavement/site conditions or to include sections that would enhance the testing program. For example, one section in California was replaced because of shrinkage cracking and popouts in the pavement and a few sections in California, Colorado, and Iowa were added as replacements or supplements.

The final 57 test sections used in the evaluation of in-place textures are listed in Table 3-2, and are shown in Figure 3-1 to indicate the respective LTPP climatic zones. (Appendix C gives more specific information on the locations of the test sections, the pavement facilities (structure, geometry) on which they exist, and the texture type, direction, and dimensions, as well as general information on the level of traffic, climatic conditions, construction date, and the date on which the pavement was opened to traffic.)

Collection of Pavement Data

Much of the information contained in Table 3-2 (and Appendix C which is available online) was acquired from

Table 3-1. Tentative texturing methods and test sites.

Basic Texture Type	Specific Texture	Section ID	
		First Option	Second Option
Dense-Graded Asphalt Concrete (DGAC)	DGAC 1-2 years old (Control 1)	IL 4-1 (4001)—I-57 Champaign (2004)	IA 8-1 (9002)—US 30 Ames/ Nevada (2004)
	DGAC 8-12 years old (Control 2)	IL 8-1 (8001)—I-74 Champaign/ Mahomet (1998)	—
Tran Tine	Marquette skewed variable tine with long turf drag	WI 5-1 (5001)—US 151 Mineral Point (2003)	IL 1-1 (5001)—I-70 Marshall (2002)
	0.5-in. spacing with long turf drag	MO 1-1 (1001)—US 36 Hannibal (2004)	GA 1-1 (---)—I-85 Atlanta (2004)
	0.75-in. spacing with long turf drag	IL 5-1 (1001)—I-55/74 Bloomington (2004)	—
	0.5-in. spacing with long turf drag	IA 1-1 (1001)—US 163 Des Moines/ Prairie City (1993)	—
	0.75-in. spacing with long turf drag	IA 5-1 (8001)—US 218 Washington/ Ainsworth (1997)	—
Long Tine	0.75-in. spacing with long turf drag	IA 2-1 (2001)—US 34 Mt. Pleasant (2004)	KS 10 (1010)—US 69 Louisburg (2004)
	0.75-in. spacing with burlap drag	IA 2-2 (2002)—US 34 Mt. Pleasant (2004)	CO 3-2 (3002)—US 287 Berthoud (2004)
	0.75-in. spacing with long turf drag	IA 1-3 (1003)—US 163 Des Moines/ Prairie City (1993)	—
Long Groove	0.75-in. spacing, 0.125-in. depth, with long turf drag	CO 3-3 (3003)—US 287 Berthoud (2004)	CA 3 (1003)—SR 58 Mojave (2003)
	0.75-in. spacing, 0.25-in. depth, with long turf drag	CA 4 (1004)—SR 58 Mojave (2003)	—
Astroturf Drag	MTD < 0.03 in	ND 2-1 (2001)—I-90 Glen Ullin (1999)	KS 12 (1012)—US 69 Louisburg (2004)
	MTD = 0.03 to 0.05 in	MN 2-1 (2003)—I-94/694 Brooklyn Park (2003)	CO 3-1 (3001)—US 287 Berthoud (2004)
Long Grind	No jacks; 0.110-in. blade spacers	KS 2 (1002)—US 69 Louisburg (2004)	AZ 1 (1001)—SR 202L Phoenix (2003)
	No jacks; 0.120-in. blade spacers	KS 4 (1004)—US 69 Louisburg (2004)	AZ 3 (1003)—SR 202L Phoenix (2003)
	No jacks; 0.130-in. blade spacers	KS 8 (1008)—US 69 Louisburg (2004)	KS 7 (1007)—US 69 Louisburg (2004)
	Jacks; 0.110-in. blade spacers	AZ 2 (1002)—SR 202L Phoenix (2003)	
	Jacks; 0.120-in. blade spacers	AZ 4 (1004)—SR 202L Phoenix (2003)	
	Jacks; 0.130-in. blade spacers	KS 5 (1005)—US 69 Louisburg (2004)	KS 6 (1006)—US 69 Louisburg (2004)
Burlap Drag		CA 4.5 (1045)—SR 58 Mojave (2003)	—
Broom Finish	Longitudinal brush	CA 5.5 (---)—SR 58 Mojave (2003)	—
EACS		QB 1-2 (---)—PH 40 Dorval (2004))	QB 1-3 (---)—PH 40 Dorval (2004)
		MI 1 (1001)—I-75 Detroit (1993)	—
Ultra-thin Bonded Wearing Course	Type A (0.1875 in.)	KS 2-1 (2001)—US 54 Batesville (2004)	—
	Type B (0.375 in.)	NC 1-1 (1001)—I-40 Hillsdale/Clemmons (2004)	KS 4-1 (4001)—I-70 Salina/Juniata (2004)
Shotpeen	MTD = 0.018 to 0.02 in.	TX 1-1 (1001)—I-20 Dallas/Duncanville (2004)	TX 2-1 (---)—I-45 Houston (2004)

1 in. = 25.4 mm

Note 1: Shaded cells represent older, more heavily trafficked sections.

Note 2: Site ID consists of original ID number followed by final ID number in parentheses.

Note 3: Second set of parentheses following highway number and city contains year of construction/texturing.

Table 3-2. Pavement test sections selected for evaluation.

STATE	HIGHWAY (DIR)	LOCATION	YEAR CONST	ORIG ID	NEW ID	TEXTURE DESCRIPTION
AZ	SR 202L (WB)	Phoenix	2003	AZ 1	1001	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers)
	SR 202L (WB)		2003	AZ 2	1002	Long DG (jacks), 0.235-in. spacing (0.11-in. spacers)
	SR 202L (WB)		2003	AZ 3	1003	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers)
	SR 202L (WB)		2003	AZ 4	1004	Long DG (jacks), 0.245-in. spacing (0.12-in. spacers)
CA	SR 58 (EB)	Mojave	2003	CA 2	1002	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers)
	SR 58 (EB)		2003	CA 3	1003	Long Groove (0.75-in. spacing, 0.125-in. depth), burlap drag
	SR 58 (EB)		2003	CA 4	1004	Long Groove (0.75-in. spacing, 0.25-in. depth), burlap drag
	SR 58 (EB)		2003	CA 4.5	1045	Long Burlap Drag
	SR 58 (EB)		2003	CA 5	1005	Long DG (no jacks), 0.23-in. spacing (0.105-in. spacers)
	SR 58 (EB)		2003	CA 7	1007	Long Groove (0.375-in. spacing, 0.25-in. depth), broom drag
	SR 58 (EB)		2003	CA 7.5	1075	Long Broom Drag
CO	I-70 (EB)	Deer Trail/Agate	1994	CO 1-7	1007	Long Groove (0.75-in. spacing, 0.125-in. depth), turf drag
	I-70 (EB)		1994	CO 1-8	1008	Long Turf Drag
	I-70 (EB)		1994	CO 1-9	1009	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag
	US 287 (SB)	Berthoud	2004	CO 3-1	3001	Long Heavy Turf Drag
	US 287 (SB)		2004	CO 3-2	3002	Long Tine (0.75-in. spacing, 0.1875-in. depth), no pretexture
	US 287 (SB)		2004	CO 3-3	3003	Long Meander Tine (0.75-in. spacing, 0.125-in. depth), no pretexture
	US 287 (NB)		2004	CO 3-5	3004	Long Groove (0.75-in. spacing, 0.125-in. depth), turf drag
	US 287 (NB)		2004	CO 3-6	3005	Long DG (no jacks), 0.22-in. spacing (0.095-in. spacers)
	US 287 (SB)		2004	CO 3-7	3006	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag
IL	I-55/74 (SB/EB)	Bloomington	2004	IL 5-1	1001	Tran Tine (0.75-in. spacing, 0.15-in. depth), turf drag
	I-57 (SB)	Champaign	2003	IL 4-1	4001	Dense-Graded AC (Superpave)
	I-70 (WB)	Marshall	2002	IL 1-1	5001	Tran Skew Tine (variable spacing, 0.15-in. depth), turf drag
	I-74 (WB)	Champaign/Mahomet	1998	IL 8-1	8001	Dense-Graded AC
IA	US 163	Des Moines/ Prairie City	1993	IA 1-2	1002	Tran Tine (0.5-in. spacing, 0.075-in. depth), turf drag
	US 163		1993	IA 1-3	1003	Long Tine (0.5-in. spacing, 0.075-in. depth), turf drag
	US 163		1993	IA 1-4	1004	Long Tine (0.75-in. spacing, 0.15-in. depth), turf drag
	US 163		1993	IA 1-6.1	1061	Tran Groove (1-in. spacing, 0.18- to 0.25-in. depth), turf drag
	US 163		1993	IA 1-7	1007	Long Turf Drag
	US 34		2004	IA 2-1	2001	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag
	US 34		2004	IA 2-2	2002	Long Tine (0.75-in. spacing, 0.125-in. depth), burlap drag
	US 218		1997	IA 5-1	8001	Tran Tine (0.75-in. spacing, 0.15-in. depth), turf drag
	US 218		1997	IA 5-2	8002	Tran Tine (0.75-in. spacing, 0.15-in. depth), turf drag
	US 30		2004	IA 8-1	9002	Dense-Graded AC (Superpave)
KS	US 69	Louisburg	2004	KS 2	1002	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers) & standard-sawed joints
	US 69		2004	KS 4	1004	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers) & single-sawed joints
	US 69		2004	KS 5	1005	Long DG (jacks), 0.255-in. spacing (0.13-in. spacers) & standard-sawed joints
	US 69		2004	KS 6	1006	Long DG (jacks), 0.255-in. spacing (0.13-in. spacers) & single-sawed joints
	US 69		2004	KS 7	1007	Long DG (no jacks), 0.255-in. spacing (0.13-in. spacers) & standard-sawed joints
	US 69		2004	KS 8	1008	Long DG (no jacks), 0.255-in. spacing (0.13-in. spacers) & single-sawed joints
	US 69		2004	KS 10	1010	Long Tine (0.75-in. spacing, 0.15-in. depth), turf drag
	US 54	Batesville	2004	KS 2-1	2001	Ultra-Thin Bonded Wearing Course (0.1875-in. NMAS)
	I-70	Salina/Juniata	2004	KS 4-1	4001	Ultra-Thin Bonded Wearing Course (0.375-in. NMAS)
MI	I-75	Detroit	1993	MI 1	1001	Exposed Aggregate Concrete
MN	US 169	Eden Prairie/Shakopee	1996	MN 1	1001	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag
	I-94/694	Brooklyn Park	2003	MN 2-1	2003	Long Broom Drag
	I-94/694	Brooklyn Center	2004	MN 2-1	2004	Long Turf Drag
	I-694	Fridley/New Brighton	1990	MN 5	5001	Long Turf Drag
	US 169	Brooklyn Park/Champlin	1996	MN 7	7001	Long Turf Drag
	US 169		1996	MN 8	8001	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag
MO	US 36	Hannibal	2004	MO 1-1	1001	Tran Tine (0.5-in. spacing, 0.125-in. depth), no pretexture
NC	I-40	Hillsdale/Clemmons	2004	NC 1	1001	Ultra-Thin Bonded Wearing Course (0.375-in. NMAS)
ND	I-94	Glen Ullin	1999	ND 2-1	2001	Long Heavy Turf Drag
	I-94		1999	ND 2-2	2002	Tran Tine (variable spacing, 0.1-in. depth), turf drag
	I-94	Valley City	2000	ND 6-1	6001	Tran Skew Tine (variable spacing, 0.15-in. depth), turf drag
TX	I-20	Duncanville/Dallas	2004	TX 1-1	1001	Shotblasted Concrete
WI	US 151	Mineral Point	2003	WI 5-1	1001	Tran Tine (variable spacing, 0.15-in. depth), turf drag

1 in. = 25.4 mm
NMAS: Nominal Maximum Aggregate Size

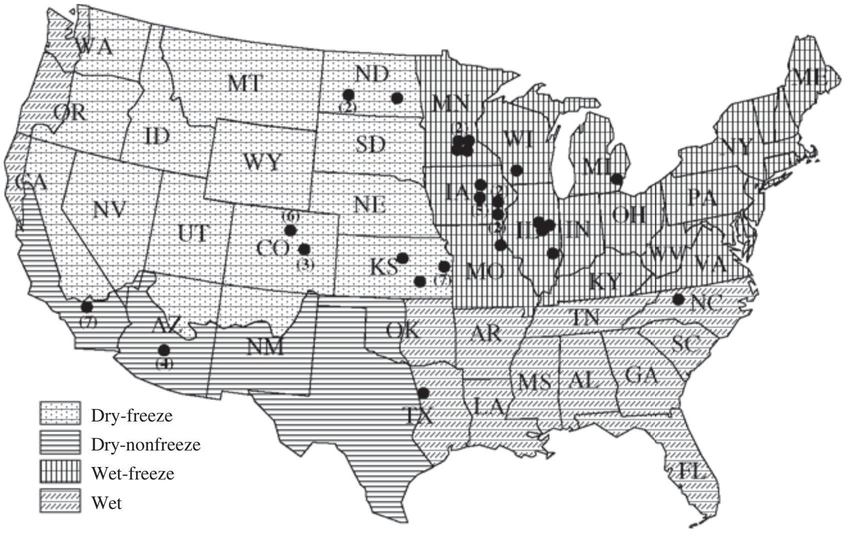


Figure 3-1. Location of test sections with respect to LTPP climatic regions.

state highway agencies, including additional information obtained while performing the on-site field testing.

To verify and augment the information obtained for the test sections, written and oral requests were made to representatives of each participating agency to obtain information on PCC aggregate and mix design properties; construction specifications, conditions, processes, and quality testing results; historical traffic levels and compositions; historical pavement conditions (distresses and smoothness); and historical friction, texture, and/or noise measurements. Simultaneous requests were also made to each agency for the conduct (and provision of resulting data) of locked-wheel friction testing (ASTM E 274, with smooth [ASTM E 524] and/or ribbed [ASTM E 501] tire) on each test section in the general timeframe of the planned friction, texture, and noise testing.

The goal of the data collection effort was to develop a comprehensive database on the existing test sections to help in analyzing relationships between friction, texture, and noise. The database was envisioned to include the following types of data:

- Design Data
  - Structure/Joint Design—Traffic, cross-section (materials and thicknesses), dowels, reinforcement, joint spacing and lane width (slab dimensions), joint seal (type, configuration, condition).
  - Mixture Design—Aggregate (type/source, properties), cement (type), mixture proportions, mixture properties (cement content, water-to-cement [w/c] ratio, slump, air content, strength, porosity).
  - Surface Design—Primary texture (type, dimensions and direction), pre-texture (type, dimensions and direction).
  - Geometric Design—Posted speed, cross-slope, grade, presence of curves, intersections, etc.
- Project/Site Information
  - Location—Highway, direction, reference/milepost/station limits, lanes, nearest city, coordinates (elevation, latitude, and longitude).
  - Setting—Urban/suburban/rural, facility type, adjacent land use (residential, commercial), special use (studded tires, snowplow use).
  - Climate (National Climate Data Center)—General LTPP descriptor (dry-freeze [DF], dry-nonfreeze [DNF], wet-freeze [WF], wet-nonfreeze [WNF]), average annual precipitation, average annual snowfall, number of days above 90°F (32°C), number of days below 32°F (0°C), freeze-thaw cycles, freezing index.
- Construction Data
  - General—Construction date, paving conditions (temperature, wind, sun, rain), traffic opening date.
  - Applicable Construction/Materials Specs—Fine and coarse aggregate requirements (hardness, uncompacted voids, fractured faces, flat/elongated, LA abrasion, Micro-Deval, acid insoluble residue [AIR], polish value), mix requirements (cement content, w/c ratio, slump, air content, strength), surface requirements (texture, smoothness, noise, friction).
  - Construction Process—PCC placement, finishing, texturing, and curing equipment/methods and timing, documented construction problems.

  - QA/QC Test Results—Aggregate properties, fresh and hardened mix properties, surface properties (initial texture dimensions and direction, initial smoothness).
- Historical Data
  - Traffic—Initial year ADT and %trucks, subsequent year ADTs and %trucks, traffic growth rate, direction and lane distribution factors.
  - Texture—Subsequent texture depth measurements, texture measurement device/method.
  - Friction—Subsequent friction measurements, friction equipment/method (device, tire type, test speed), friction test conditions (air temp, wind, sun), equipment calibration (date, location, speed, 524 conversion intercept and slope).
  - Accidents—Wet-to-dry crash rates.
  - Noise—Near-field SI, interior vehicle noise L_{eq}, far-field pass-by noise.
  - Smoothness—Subsequent IRI measurements, smoothness measuring equipment/method.
  - Distress—Faulting, cracking, spalling.

Test Section Descriptions

Brief descriptions of the 57 selected test sections are provided in Appendix C. The sections represent an array of formed and cut (fresh and hardened) concrete pavement surface textures, as well as some asphalt surfacings with different mix characteristics. The sections are mostly new (<5 years in age) and typically are located on 2- or 4-lane highway facilities. The sections represent a range of traffic and climatic conditions. Several of the sections were built as part of an agency study on pavement texturing.

Texture, Friction, and Noise Testing of Existing Texture Test Sections

Field Testing Protocol

The following specific texture, friction, and noise tests (and their corresponding outputs) were planned for the selected test sections:

- Texture (macro-texture)
  - CT Meter (ASTM E 2157)—MPD and RMS.
  - High-Speed Texture Profiler (International Cybernetics Corporation [ICC] Model MDR 4081-T 64-Hz laser texture system mounted on Honda CR-V test vehicle)—MPD, EMTD (also capable of generating International Roughness Index [IRI] and Ride Number [RN]). EMTD computed according to ASTM E 1845:

$$\mathrm{EMTD} = 0.0079 + 0.8 \times \mathrm{MPD} \quad (\text{U.S. Customary units}) \qquad \text{Eq. 3-1a}$$

$$\mathrm{EMTD} = 0.2 + 0.8 \times \mathrm{MPD} \ (\text{SI units}) \qquad \text{Eq. 3-1b}$$

- Friction (micro-texture)
  - DF Tester (ASTM E 1911)—DFT(20) (also capable of generating friction numbers at other speeds, such as DFT(40), DFT(60), and DFT(80)).
- Noise
  - Near-Field Noise (GM standard), as measured with proprietary single-probe receptor and noise equipment, and Goodyear Aquatred III test tire, mounted on an all-wheel drive Honda CR-V test vehicle (see Figure 3-2)—SI.
  - Interior Vehicle Noise (SAE J1477), as measured with proprietary receptor and noise equipment mounted in the interior of the Honda CR-V test vehicle—L_{eq}.
  - Far-Field CPB Noise (in accordance with ISO 11819, but with fixed vehicle), as measured with proprietary wayside receptor and noise equipment—L_{max}.

Collection of high-speed texture data and the three forms of noise data required no lane closure, whereas collection of micro-texture (DF Tester) and macro-texture (CT Meter) required traffic control and full lane closure. The following protocols were developed and followed for these tests:

- High-Speed Texture—Macro-texture measurements will be made in the right wheelpath (18 to 30 in. [460 to 760 mm] from the outside lane edge, depending on lane width) at 60 mi/hr (97 km/hr). If it can be safely accomplished, texture measurements also will be collected in the lane center to evaluate the effects of wear on texture durability. Steps in the macro-texture measurement process will include
  1. Set markers at the roadside to define the test section limits.
  2. Warm up tires for at least 10 minutes and check the tire pressure.
  3. Make three passes over the site.

Figure 3-2. SI horizontal single-probe configuration.

4. Collect data with the right wheel in the lane center, where this can be safely accomplished.
5. Review the texture depths and profiles for each pass for reasonableness and precision; make repeat runs, as appropriate.
6. Back up the data.

- Near-Field Noise Measurement (SI)—Prior to data collection, the equipment will be calibrated according to the manufacturer's recommendations. SI noise testing will be conducted at a speed of 60 mi/hr (97 km/hr) using a Goodyear Aquatred III test tire (ASTM E 1136) aligned in the right wheelpath (18 to 30 in. [460 to 760 mm] from the outside lane edge, depending on lane width). If it can be safely accomplished, SI measurements also will be collected with the test tire aligned in the lane center. The process includes the following steps:
  1. Set markers at the roadside to define the test section limits.
  2. Position the microphone probe at the front of the test tire.
  3. Warm up tires for at least 10 minutes at highway speeds and check the tire pressure.
  4. Make three passes over the site with the test tire aligned in the right wheelpath.
  5. Collect additional data with the test tire aligned at the lane center.
  6. Re-position the microphone probe to the rear of the test tire.
  7. Make three passes each with the test tire aligned in the right wheelpath and at the lane center, respectively.
  8. Review the noise spectra and SI levels for each pass for reasonableness and precision; make repeat runs, as appropriate.
  9. Back up the data.
- Interior Noise Measurement (L_{eq})—Interior noise equipment will be calibrated according to the manufacturer's recommendations. Noise data will be collected using a single microphone above the passenger seat, in accordance with SAE J1477. This method entails the following anticipated setup and steps:
  1. Make sure all windows are up and all vehicle ventilation and the radio are turned off.
  2. Adjust the seat and headrest to mid position.
  3. Position the microphone securely 2.25 ft (0.7 m) above the intersection of the passenger seat surface and the seat back. Orient the microphone facing forward.
  4. Check and document the background noise (stationary and vehicle off).
  5. Ensure that wind speed is less than 11 mi/hr (18 km/hr) and that ambient air temperature is between 23 and 95°F (–5 and 35°C). If not, wait until winds die down sufficiently and/or temperature is in range.
  6. Record the wind speed and direction, air temperature, and driving direction.
  7. Collect data while passing the test site at 60 mi/hr (97 km/hr).
  8. Check data for reasonableness and completeness.
  9. Ensure that the measured noise is at least 10 dB greater than the background noise level.
  10. Repeat tests until three sets of precision data are obtained.
  11. Compute the overall average "A" weighted sound level.
  12. Compute the overall average ⅓ octave A-weighted sound levels.
  13. Compute the FFT frequency spectrum using a 3-5 Hz resolution frequency analyzer.
  14. Back up the data.
- Far-Field CPB Noise Measurement (L_{max})—The CPB system will be calibrated according to the recommended manufacturer's procedures. Testing will be done using the same vehicle and test tires (Aquatred III tires mounted on both the front and rear on the side closest to the far-field microphone) used in the SI testing. Steps that will be followed in this data collection effort include the following:
  1. Confirm roadside location selection meets the requirements of ISO-11819-1.
  2. Ensure that the environmental conditions are adequate for testing.
  3. Set up the microphones at 25 ft (7.5 m) from the vehicle center at an elevation of 5 ft (1.5 m) above the outside lane elevation.
  4. Ensure that the entire surface between the vehicle and microphone has consistent attenuation using plywood strips as necessary.
  5. Set up a calibrated thermometer for air temperature measurements.
  6. Set up an anemometer for wind speed and direction measurement.
  7. Set up the data collection and storage board.
  8. Make three vehicle passes with the same tires used in the near-field measurements.
  9. Check the data for reasonableness and precision; make repeat runs, as appropriate.
  10. Back up the data.
- CT Meter Macro-texture Measurements—Longitudinal and transverse macro-texture measurements will be made in at least five locations in both the right wheelpath (18 to 30 in. [460 to 760 mm] from the outside lane edge, depending on lane width) and the lane center, in accordance with ASTM E 2157. Areas of the pavement with sufficient length and consistent noise and texture qualities will be singled-out as a test section. Representative measurements will be collected at locations that exhibit different tine channel dimensions, texture properties, or noise properties. All data will be checked for reasonableness and precision, and tests

will be repeated as appropriate. Prior to leaving the site, the data will be backed up to a CD. If CT Meter equipment problems are encountered and cannot be resolved, the sand patch test method (ASTM E 965) will be used.
- DF Tester Friction/Micro-texture Measurements—Micro-texture properties of the pavement surfaces will be measured in accordance with ASTM E 1911. Data will be collected at the same locations as the CT Meter macro-texture measurements. All data will be checked for reasonableness and precision, and tests will be repeated as appropriate. All data will be backed up prior to leaving the site.

Formal Testing

Prior to formal testing of the selected test sections, extensive training was obtained on the different testing equipment. In addition, various calibrations and accuracy checks of the Honda CR-V SI system were performed using a certified SI system (installed on a Subaru Outback) for comparison. As part of this testing, a series of repeat runs were made by both systems on each of two asphalt pavement sections and two longitudinally tined concrete sections. Results showed negligible differences in measurements of pink noise and a slightly lower (<1 dB(A) difference) overall average SI measurement taken by the certified system. This difference was partly attributed to differences in the lateral positioning of the two test vehicles during testing and to differences in the vehicle suspension and wheel camber characteristics.

Upon coordination of traffic control with the appropriate personnel in each SHA, formal testing commenced. Measurements were conducted during the June 6 to November 5, 2005 time period. Table 3-3 lists the specific dates of testing for each test section. Figures 3-3 and 3-4 illustrate the specific locations for texture, friction, and noise measurements on the test sections.

Agency-Supplied Friction Data

To supplement the DF Tester friction/micro-texture data, the participating state agencies conducted locked-wheel friction testing (ASTM E 274) using both a smooth (ASTM E 524) and ribbed tire (ASTM E 501) on each test section and provided the resulting data. Table 3-4 lists the high-speed friction data provided by each state.

As indicated, data were not provided by some states. The provided data were in most cases for both smooth and ribbed tires in at least one of the wheelpaths. In some cases, data for a locked-wheel tester or one of the specified types of tires were not provided because of agency practices not to perform these tests. All locked-wheel test data were collected at 40 mi/hr (64 km/hr).

Texture, Friction, and Noise Test Results

This section presents the results of the texture, friction, and noise tests in terms of summaries of the key outputs from these tests as well as other relevant indexes. These indexes and the equations for their computations are as follows:

- CT Meter MTD developed using CT Meter MPD and the following NASA/Wallops equation (Henry, 2000):

$$\mathrm{MTD} = 0.952 \times \mathrm{MPD} + 0.0036 \quad (\text{US Customary units}) \qquad \text{Eq. 3-2a}$$

$$\mathrm{MTD} = 0.952 \times \mathrm{MPD} + 0.091 \quad (\text{SI units}) \qquad \text{Eq. 3-2b}$$

- Texture Orientation (TO) determined based on the ratio of MPD to RMS, as measured using the CT Meter. In general, ratios greater than 1.05 to 1.10 are categorized as positive TO. They are representative of an aggressive, protruding surface, such as a chip seal surface. Ratios less than 0.90 to 0.95 are categorized as negative TO. They are representative of a flat, pocketed surface, such as HMA or grooved PCC. Ratios between these two sets of values are considered to have neutral TO.

$$\text{Texture Ratio } (\mathrm{TR}) = \mathrm{MPD}/\mathrm{RMS} \qquad \text{Eq. 3-3}$$

- International Friction Index (IFI) Friction Number F(60), as given in ASTM E 1960:

$$F(60) = A + B \times FR(S) \times e^{([S-60]/S_P)} + C \times TX \quad (\text{SI units}) \qquad \text{Eq. 3-4}$$

$$S_P = a + b \times TX \quad (\text{SI units}) \qquad \text{Eq. 3-5}$$

where
$FR(S)$ = Friction number measured by friction device at speed S.
S = Friction test speed, km/hr.
S_P = Speed number.
TX = Macro-texture measurement.
A, B, C = Friction device calibration constants.
a, b = Macro-texture method calibration constants.

Using the A, B, and C calibration constants given in ASTM E 1960 for the DF Tester and the locked-wheel friction tester

Table 3-3. Dates of friction, texture, and noise measurements.

State	Highway	Location	Section ID	Texture (high-speed)	Noise (near field)	Noise (interior)	Noise (far field)	Texture (CTM)	Friction (DFT)
AZ	SR 202	Phoenix	1001, 1002, 1003, 1004	11/16/05	11/16/05	11/16/05	—	11/14/05 – 11/15/05	11/14/05 – 11/15/05
CA	SR 58	Mojave	1002, 1003, 1004, 1045, 1005, 1007, 1075	11/11/05	11/11/05	11/11/05	11/9/05*	11/9/05 – 11/10/05	11/9/05 – 11/10/05
CO	I-70	Agate/Deer Trail	1007, 1008, 1009	10/21/05	10/21/05	10/21/05	—	10/22/05	10/22/05
CO	US 287	Berthoud	1001, 1002, 1003, 1004, 1005, 1006	10/26/05 – 10/27/05	10/26/05 – 10/27/05	10/26/05 – 10/27/05	10/26/05*	10/23/05 – 10/25/05	10/23/05 – 10/25/05
IL	I-55/74	Bloomington	1001	8/30/05	8/30/05	8/30/05	8/30/05	—	—
IL	I-57	Champaign	4001	8/4/05	8/4/05	8/4/05	8/4/05	8/24/05	8/24/05
IL	I-70	Marshall	5001	8/25/05	8/25/05	8/25/05	—	8/26/05	8/26/05
IL	I-74	Champaign/ Mahomet	8001	8/4/05	8/4/05	8/4/05	—	8/5/05	8/5/05
IA	US 163	Des Moines/ Prairie City	1002, 1003, 1003, 1061, 1007	8/17/05	8/17/05	8/17/05	—	—	—
IA	US 34	Mt. Pleasant	2001, 2002	8/15/05	8/15/05	8/15/05	6/7/06*	6/6/06 – 6/7/06	6/6/06 – 6/7/06
IA	US 218	Washington	8001, 8002	8/16/05	8/16/05	8/16/05	—	—	—
IA	US 30	Ames/Nevada	9002	8/17/05	8/17/05	8/17/05	—	—	—
KS	US 69	Louisburg	1002, 1004, 1005, 1006, 1007, 1008, 1010	9/25/05	9/25/05	9/25/05	10/18/05*	9/25/05	9/25/05
KS	US 54	Batesville	2001	10/19/05	10/19/05	10/19/05	—	—	—
KS	I-70	Salina/ Juniata	4001	9/27/05	9/27/05	9/27/05	9/27/05	9/27/05	9/27/05
MI	I-75	Detroit	1001	10/12/05	10/12/05	10/12/05	—	—	—
MN	US 169	Eden Prairie/ Shakopee	1001	9/10/05	9/10/05	9/10/05	—	9/10/05	9/10/05
MN	I-94/694	Brooklyn Park/ Brooklyn Center	2003, 2004	9/10/05	9/10/05	9/10/05	—	9/10/05	9/10/05
MN	I-694	Fridley/ New Brighton	5001	9/9/05	9/9/05	9/9/05	—	—	—
MN	US 169	Brooklyn Park/ Champlin	7001, 8001	9/9/05	9/9/05	9/9/05	—	9/16/05	9/16/05
MO	US 36	Hannibal	1001	8/8/05	8/8/05	8/8/05	8/8/05	8/8/05	8/8/05
NC	I-40	Hillsdale/ Clemmons	1001	7/16/05	7/16/05	7/16/05	—	7/16/05	7/16/05
ND	I-94	Glen Ullin	2001, 2002	9/13/05	9/13/05	9/13/05	—	9/13/05	9/13/05
ND	I-94	Valley City	6001	9/11/05	9/11/05	9/11/05	—	9/11/05	9/11/05
TX	I-20	Dallas/ Duncanville	1001	11/18/05	11/18/05	11/18/05	11/19/05	11/19/05	11/19/05
WI	US 151	Mineral Point	5001	9/6/05	9/6/05	9/6/05	9/6/05	9/6/05	9/6/05

* Control pass-by noise measurement only.

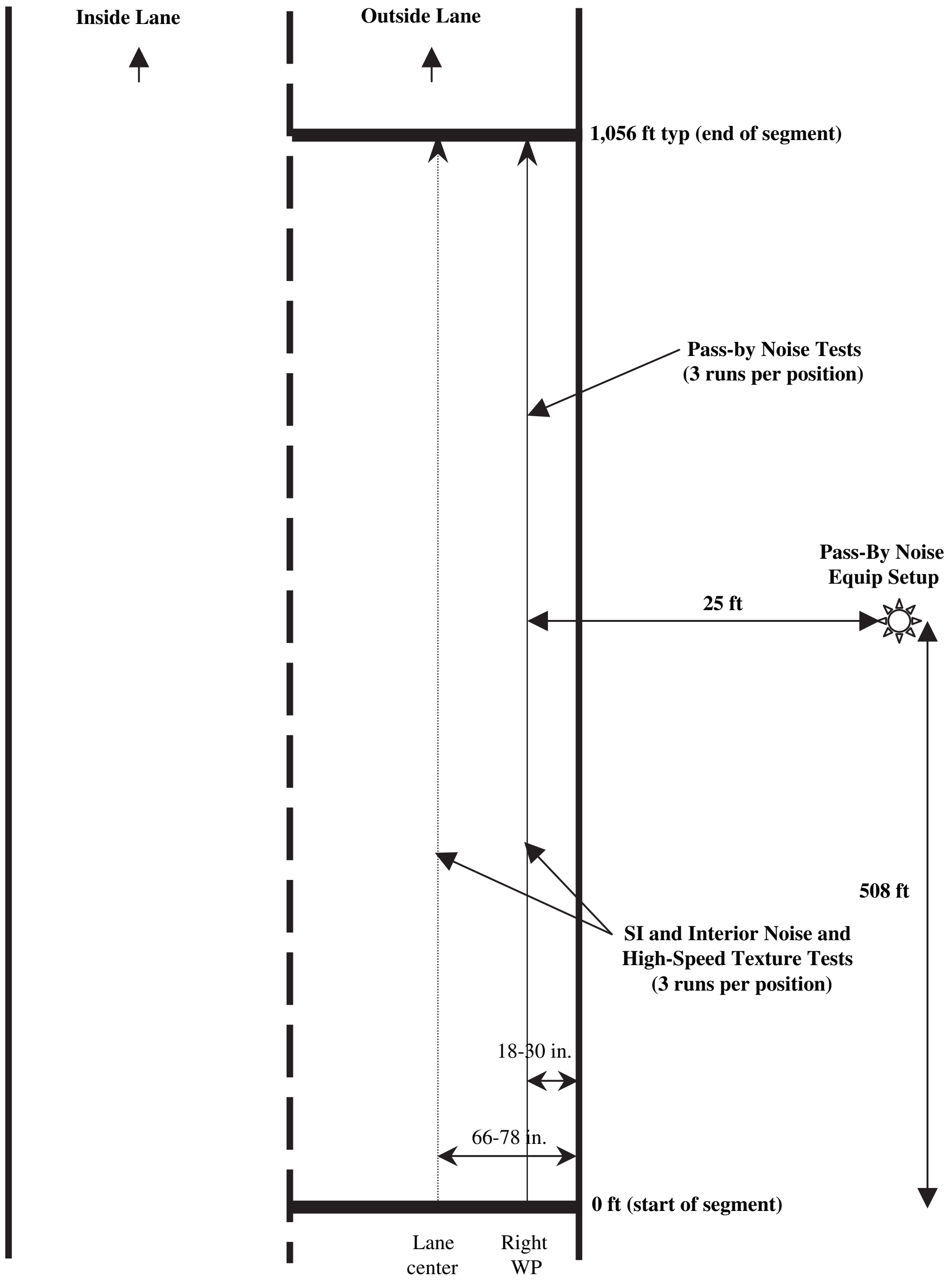


Figure 3-3. Location of standard noise and high-speed texture testing measurements.

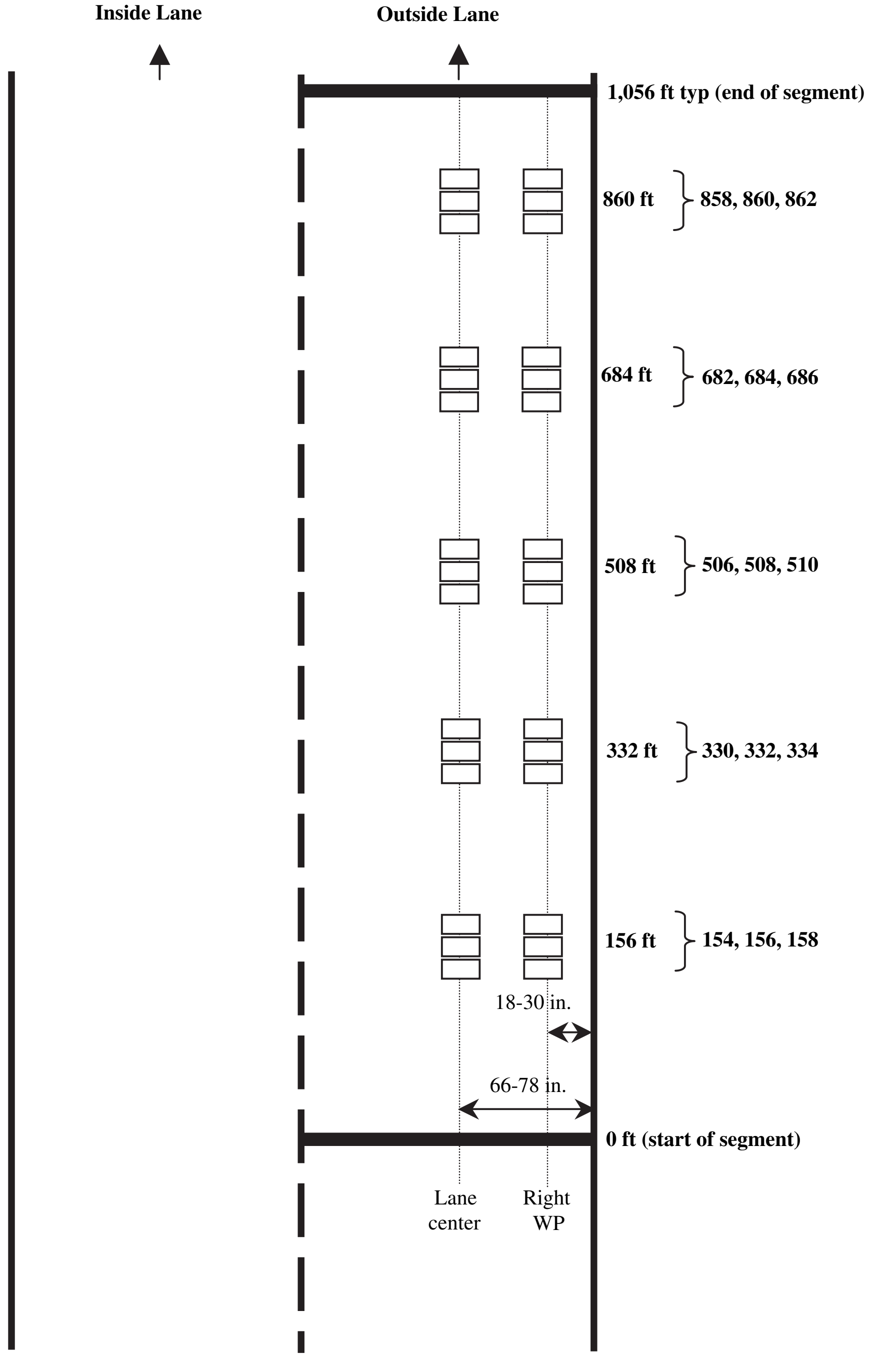


Figure 3-4. Location of standard DF Tester and CT Meter test measurements.

Table 3-4. Summary of high-speed friction tests performed by participating agencies.

State	Highway	Location	Section ID	Date of Testing	Friction Tester Description
AZ	SR 202	Phoenix	1001, 1002, 1003, 1004	5/17/06	Dynatest/KJ Law Fixed-Slip Runway Friction Tester (RFT)—foot-by-foot continuous measurement lane center at 60 mi/hr.
IL	I-55/74	Bloomington	1001	9/21/06	Locked-Wheel Friction Tester (ASTM E 274) with both smooth (ASTM E 524) and ribbed (ASTM E 501) tires—Three tests per test section in left wheelpath at 40 mi/hr.
IL	I-57	Champaign	4001	9/18/06	
IL	I-70	Marshall	5001	9/19/06	
IL	I-74	Champaign/ Mahomet	8001	9/18/06	
IA	US 163	Des Moines/ Prairie City	1002, 1003, 1003, 1061, 1007	9/19/05	Locked-Wheel Friction Tester (ASTM E 274) with both smooth (ASTM E 524) and ribbed (ASTM E 501) tires—Two tests per test section in left wheelpath at 40 mi/hr.
IA	US 34	Mt. Pleasant	2001, 2002	9/12/05	
IA	US 218	Washington	8001, 8002	9/12/05	
IA	US 30	Ames/Nevada	9002	9/15/05	
KS	US 69	Louisburg	1002, 1004, 1005, 1006, 1007, 1008, 1010	11/21/05	Locked-Wheel Friction Tester (ASTM E 274) with ribbed tire (ASTM E 501)—Three tests per test section in left wheelpath at 40 mi/hr.
KS	US 54	Batesville	2001	12/23/05	Locked-Wheel Friction Tester (ASTM E 274) with both smooth (ASTM E 524) and ribbed (ASTM E 501) tires—Five tests per test section in left wheelpath at 40 mi/hr.
KS	I-70	Salina/ Juniata	4001	12/14/05	
MI	I-75	Detroit	1001	10/25/05	Locked-Wheel Friction Tester (ASTM E 274) with smooth tire (ASTM E 524)—Four tests per test section in right wheelpath at 40 mi/hr.
NC	I-40	Hillsdale/ Clemmons	1001	1/10/06	Locked-Wheel Friction Tester (ASTM E 274) with ribbed tire (ASTM E 501)—Three tests per test section at lane center at 40 mi/hr.
TX	I-20	Dallas/ Duncanville	1001	8/4/06	Locked-Wheel Friction Tester (ASTM E 274) with both smooth (ASTM E 524) and ribbed (ASTM E 501) tires—Four tests per test section at lane center and in both wheelpaths at 40 mi/hr.
WI	US 151	Mineral Point	5001	6/29/06	Locked-Wheel Friction Tester (ASTM E 274) with both smooth (ASTM E 524) and ribbed (ASTM E 501) tires—Two tests per test section at lane center and in left wheelpath at 40 mi/hr.

1 mi/hr = 1.61 km/hr

Note: No data were provided for sections in California, Colorado, Minnesota, Missouri, and North Dakota.

with ribbed and smooth tires, and the a and b coefficients given in ASTM E 1960 for MPD, the following equations were used to compute IFI F(60) values:

Using DFT(20) from DF Tester and high-speed profiler MPD:

$$F(60) = 0.081 + 0.732 \times DFT(20) \times e^{([20-60]/S_P)} + 0 \times MPD \text{ (SI units)} \qquad \text{Eq. 3-6}$$

$$S_P = 14.2 + 89.7 \times MPD \text{ (in mm)} \qquad \text{Eq. 3-7}$$

Using FN40R (i.e., FN(65)R) from locked-wheel tester with ribbed tire (ASTM E 274 and E 501) and high-speed profiler MPD:

$$F(60) = -0.023 + 0.607 \times FN(65)R \times e^{([65-60]/S_P)} + 0.098 \times MPD \text{ (SI units)} \qquad \text{Eq. 3-8}$$

$$S_P = 14.2 + 89.7 \times MPD \text{ (SI units)} \qquad \text{Eq. 3-9}$$

Using FN40S (i.e., FN(65)S) from locked-wheel tester with smooth tire [ASTM E 274 and E 524]) and high-speed profiler MPD:

$$F(60) = 0.045 + 0.925 \times FN(65)S \times e^{([65-60]/S_P)} + 0 \times MPD \text{ (SI units)} \qquad \text{Eq. 3-10}$$

$$S_P = 14.2 + 89.7 \times MPD \text{ (SI units)} \qquad \text{Eq. 3-11}$$

Table 3-5 lists the mean texture values based on measurements from the right wheelpath and the lane center, the mean micro-texture and friction values, and the mean noise levels, as measured at the pavement–tire interface, in the vehicle interior, and at the side of the road for each test section. (Detailed results of the texture, friction, and noise testing are presented in Appendix D which is available online.)

Table 3-5. Texture, friction, and noise data.

STATE	SECT ID	HWY	CONST YEAR	TEXTURE DESCRIPTION	HS PROFILER[1]		CT METER[1]			DF TESTER[1]		LOCKED-WHEEL[1]		SI NOISE, DB(A)[1]	INT NOISE, DB(A)[1]	CPB NOISE, DB(A)
					MPD, mm	EMTD, mm	MPD, mm	MTD, mm	TR	DFT(20)	F(60)	FN40S[2]	F(60)			
AZ	04-1001	SR 202L	2003	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers)	0.64	0.72	0.99	1.06	2.30	80.5	41.73	NA	NA	104.5	70.4	NA
	04-1002	SR 202L	2003	Long DG (jacks), 0.235-in. spacing (0.11-in. spacers)	0.64	0.71	1.01	1.09	2.34	77.0	40. 01	NA	NA	105.7	71.8	NA
	04-1003	SR 202L	2003	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers)	0.89	0.92	1.58	1.65	2.45	81.0	46.89	NA	NA	106.35	73.5	NA
	04-1004	SR 202L	2003	Long DG (jacks), 0.245-in. spacing (0.12-in. spacers)	0.61	0.69	0.70	0.78	1.73	67.5	34. 37	NA	NA	104.8	70.1	NA
CA	06-1002	SR 58	2003	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers)	0.61	0.69	0.74	0.81	1.87	72.0	36.92	NA	NA	105.65	68.85	NA
	06-1003	SR 58	2003	Long Groove (0.75-in. spacing, 0.125-in. depth), burlap drag	0.70	0.78	1.04	1.10	0.72	71.5	39.06	NA	NA	104.8	69.45	NA
	06-1004	SR 58	2003	Long Groove (0.75-in. spacing, 0.25-in. depth), burlap drag	0.78	0.94	1.23	1.30	0.54	73. 0	41.46	NA	NA	105.25	69.9	NA
	06-1045	SR 58	2003	Long Burlap Drag	0.53	0.63	0.27	0.35	1.70	71.5	35.64	NA	NA	104.45	69.3	NA
	06-1005	SR 58	2003	Long DG (no jacks), 0.23-in. spacing (0.105-in. spacers)	0.56	0.65	0.73	0.81	1.83	68.5	34.82	NA	NA	104.45	67.85	NA
	06-1007	SR 58	2003	Long Groove (0.375-in. spacing, 0.25-in. depth), broom drag	0.64	0.71	1.53	1.58	0.87	67.5	35.98	NA	NA	105.6	70.9	NA
	06-1075	SR 58	2003	Long Broom Drag	0.64	0.71	0.25	0.34	1.77	66.0	24.19	NA	NA	105.25	71	NA
CO	08-1007	I-70	1994	Long Groove (0.75-in. spacing, 0.125-in. depth), turf drag	NA	NA	1.28	1.35	0.94	74.5	45.61	NA	NA	105.9	69.4	NA
	08-1008	I-70	1994	Long Turf Drag	NA	NA	0.27	0.36	1.70	75.0	38.16	NA	NA	104.4	68.6	NA
	08-1009	I-70	1994	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	NA	NA	0.82	0.89	1.07	76.5	45.80	NA	NA	106.1	69.8	NA
	08-3001	US 287	2004	Long Heavy Turf Drag	NA	NA	NA	NA	NA	92.0	52.41	NA	NA	103	69.7	77.85
	08-3002	US 287	2004	Long Tine (0.75-in. spacing, 0.1875-in. depth), no pretexture	NA	NA	NA	NA	NA	95.0	54.56	NA	NA	104.3	70.3	NA
	08-3003	US 287	2004	Long Meander Tine (0.75-in. spacing, 0.125-in. depth), no pretexture	NA	NA	NA	NA	NA	92.0	56.01	NA	NA	104.4	71.3	NA
	08-3004	US 287	2004	Long Groove (0.75-in. spacing, 0.125-in. depth), turf drag	NA	NA	NA	NA	NA	81.0	44.36	NA	NA	104.3	69.21	78.65
	08-3005	US 287	2004	Long DG (no jacks), 0.22-in. spacing (0.095-in. spacers)	NA	NA	NA	NA	NA	89.0	43.79	NA	NA	102.8	68.1	NA
	08-3006	US 287	2004	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	NA	NA	NA	NA	NA	89.0	50.70	NA	NA	103.8	69.9	NA
IL	17-1001	I-55/74	2004	Tran Tine (0.75-in. spacing, 0.15-in. depth), turf drag	1.00	1.01	NA	NA	NA	NA	NA	32.3	35.83	106.85	70.9	NA
	17-4001	I-57	2003	Dense-Graded AC (Superpave)	NA	NA	0.50	0.57	1.26	66.0	38.85	40.0	NA	102.2	68.1	76.8
	17-5001	I-70	2002	Tran Skew Tine (variable spacing, 0.15-in. depth), turf drag	0.67	0.74	0.47	0.55	1.27	71.5	37.96	30.0	34.11	104.45	69.05	80.95
	17-8001	I-74	1998	Dense-Graded AC	NA	NA	0.68	0.76	1.28	67.0	41.26	38.7	NA	104.3	68.8	NA
IA	19-1002	US 163	1993	Tran Tine (0.5-in. spacing, 0.075-in. depth), turf drag	1.06	1.05	NA	NA	NA	NA	NA	33.0	36.56	106.35	71.2	NA
	19-1003	US 163	1993	Long Tine (0.5-in. spacing, 0.075-in. depth), turf drag	1.03	1.03	NA	NA	NA	NA	NA	37.9	41.37	105.4	71.2	NA
	19-1004	US 163	1993	Long Tine (0.75-in. spacing, 0.15-in. depth), turf drag	1.03	1.03	NA	NA	NA	NA	NA	39.9	43.31	106.1	72.2	NA
	19-1061	US 163	1993	Tran Groove (1-in. spacing, 0.18- to 0.25-in. depth), turf drag	1.05	1.04	NA	NA	NA	NA	NA	32.7	36.25	109	74.2	NA
	19-1007	US 163	1993	Long Turf Drag	1.07	1.06	NA	NA	NA	NA	NA	13.7	17.79	105.7	72.1	NA
	19-2001	US 34	2004	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	NA	NA	0.63	0.69	1.31	43.0[3]	27.31[3]	49.2	52.91	103.8	71.2	78.6
	19-2002	US 34	2004	Long Tine (0.75-in. spacing, 0.125-in. depth), burlap drag	NA	NA	0.70	0.75	1.13	38.5[3]	26.28[3]	47.7	51.11	105.3	72.2	80.55
	19-8001	US 218	1997	Tran Tine (0.75-in. spacing, 0.15-in. depth), turf drag	0.99	0.99	NA	NA	NA	NA	NA	53.5	56.46	107.9	71.4	NA
	19-8002	US 218	1997	Tran Tine (0.75-in. spacing, 0.15-in. depth), turf drag	NA	NA	NA	NA	NA	NA	NA	45.1	48.53	107.5	69.9	NA
	19-9002	US 30	2004	Dense-Graded AC (Superpave)	NA	NA	NA	NA	NA	NA	NA	26.7	31.21	103.5	68.5	NA

(continued on next page)

Table 3-5. (Continued).

STATE	SECT ID	HWY	CONST YEAR	TEXTURE DESCRIPTION	HS PROFILER[1]		CT METER[1]			DF TESTER[1]		LOCKED-WHEEL[1]		SI NOISE, DB(A)[1]	INT NOISE, DB(A)[1]	CPB NOISE, DB(A)
					MPD, mm	EMTD, mm	MPD, mm	MTD, mm	TR	DFT(20)	F(60)	FN40S[2]	F(60)			
KS	20-1002	US 69	2004	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers) & standard-sawed joints	0.53	0.63	0.77	0.85	2.15	60.5	31.57	43.2 (FN40R)	31.14	104.65	72.2	NA
	20-1004	US 69	2004	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers) & single-sawed joints	0.62	0.70	0.79	0.86	2.29	60.5	33.34	43.3 (FN40R)	31.84	105.5	72.55	77.9
	20-1005	US 69	2004	Long DG (jacks), 0.255-in. spacing (0.13-in. spacers) & standard-sawed joints	0.63	0.71	0.95	1.01	2.13	64.0	34.74	46.0 (FN40R)	33.56	105.3	72.75	NA
	20-1006	US 69	2004	Long DG (jacks), 0.255-in. spacing (0.13-in. spacers) & single-sawed joints	0.63	0.70	0.97	1.03	2.13	62.5	34.27	45.6 (FN40R)	33.36	105.4	72.65	NA
	20-1007	US 69	2004	Long DG (no jacks), 0.255-in. spacing (0.13-in. spacers) & standard-sawed joints	0.61	0.69	0.98	1.04	2.21	62.5	34.08	47.0 (FN40R)	34.19	105.1	72.95	NA
	20-1008	US 69	2004	Long DG (no jacks), 0.255-in. spacing (0.13-in. spacers) & single-sawed joints	0.86	0.90	0.91	0.98	2.18	64.5	38.96	45.9 (FN40R)	35.52	106.4	74.1	NA
	20-1010	US 69	2004	Long Tine (0.75-in. spacing, 0.15-in. depth), turf drag	0.56	0.65	0.65	0.72	1.22	70.0	35.95	50.8 (FN40R)	36.26	105.35	73.4	NA
	20-2001	US 54	2004	Ultra-Thin Bonded Wearing Course (0.1875-in. NMAS)	NA	NA	NA	NA	NA	NA	NA	39.9	42.98	100.6	69.3	NA
	20-4001	I-70	2004	Ultra-Thin Bonded Wearing Course (0.375-in. NMAS)	1.20	1.18	0.94	1.01	1.26	78.5	47.6	53.4	56.26	103.1	70.4	79.15
MI	26-1001	I-75	1993	Exposed Aggregate Concrete	NA	NA	NA	NA	NA	NA	NA	22.2	26.38	108	70.1	NA
MN	27-1001	US 169	1996	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	0.77	1.01	NA	NA	NA	NA	NA	NA	NA	105	69.6	NA
	27-2003	I-94/694	2003	Long Broom Drag	0.59	0.67	NA	NA	NA	NA	NA	NA	NA	105.7	71.15	NA
	27-2004	I-94/694	2004	Long Turf Drag	0.58	0.67	NA	NA	NA	NA	NA	NA	NA	104.9	69.5	NA
	27-5001	I-694	1990	Long Turf Drag	0.58	0.66	NA	NA	NA	NA	NA	NA	NA	106.5	71.8	NA
	27-7001	US 169	1996	Long Turf Drag	0.61	0.69	0.40	0.48	1.47	71.5	37.67	NA	NA	106.8	71.45	NA
	27-8001	US 169	1996	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	0.89	1.84	0.91	0.98	1.12	75.0	43.65	NA	NA	108.15	72.8	NA
MO	29-1001	US 36	2004	Tran Tine (0.5-in. spacing, 0.125-in. depth), no pretexture	1.09	1.07	0.64	0.71	1.16	68.0	42.23	NA	NA	104.9	69.1	80.25
NC	37-1001	I-40	2004	Ultra-Thin Bonded Wearing Course (0.375-in. NMAS)	NA	NA	0.82	0.88	1.25	65.5	42.98	50.7	53.30	NA	NA	NA
ND	38-2001	I-94	1999	Long Heavy Turf Drag	0.86	0.89	0.57	0.65	1.22	81.0	46.06	NA	NA	110.3	73.1	NA
	38-2002	I-94	1999	Tran Tine (variable spacing, 0.1-in. depth), turf drag	0.61	0.69	0.39	0.47	1.77	78.5	40.21	NA	NA	105.5	68.85	NA
	38-6001	I-94	2000	Tran Skew Tine (variable spacing, 0.15-in. depth), turf drag	0.90	0.93	0.65	0.73	1.22	67.5	40.20	NA	NA	108.5	74.4	NA
TX	48-1001	I-20	2004	Shotblasted Concrete	0.87	0.90	0.69	0.78	1.76	46.5	30.33	25.3	29.18	108.05	72.55	84
WI	55-1001	US 151	2003	Tran Tine (variable spacing, 0.15-in. depth), turf drag	NA	NA	0.82	0.88	1.02	80.5	46.49	51.0	54.27	107.3	71.3	82.6

[1] Mean values based on right wheelpath and lane center measurements.
[2] Smooth tire friction number, unless otherwise noted.
[3] Values substantially lower than expected.
NA=Not available

CHAPTER 4

Construction and Evaluation of New Test Sections

Selecting Surface Textures for Detailed Evaluation

By using a systematic procedure to rank the friction, texture, and noise characteristics of existing texture test sections, a few forms of textures were identified as having good potential to provide adequate friction and reduced noise characteristics. These textures, described in Table 4-1, were selected for additional evaluation in newly constructed test sections as part of a paving project. The evaluation (1) examined the constructability, performance, and durability of the different textures; (2) further analyzed their performance and durability; and (3) helped identify rational requirements for texture, friction, and noise.

Identification of a Candidate Paving Project

Several state highway agencies were asked about their ability to incorporate the selected texturing types in a paving project and support the field work. Although a few states expressed interest and identified possible projects, they were not selected because of construction schedule and other constraints. Subsequently, an offer by the Illinois State Toll Highway Authority (ISTHA, now the Illinois Tollway) to construct the test sections as part of a new alignment construction project in the southwest suburbs of Chicago was accepted. Details of the subject project and the construction of the various test sections are provided in the following sections.

Project Overview

The PCC paving project selected for constructing and testing the selected surface textures was the South Extension of the I-355 North-South Tollway between I-55 and I-80 near Joliet, Illinois. This project is six lanes wide and 12.5 mi (20.1 km) long and contains intermittent interchanges and an open road-style toll plaza. The one-way average daily traffic (ADT) in 2008 was estimated to be 53,000 veh/day, with 7 percent commercial vehicles, and is expected to grow to 84,000 veh/day by 2030.

Construction on this multi-contracted project commenced in late 2004 with land clearing operations. Major earthwork began in 2005, and bridge and interchange work and general grading operations started in 2006. Aggregate subbase for the mainline roadway was placed in fall 2006 and spring 2007. Hot mix asphalt (HMA) base and PCC surface paving operations were begun in April 2007 and completed in July 2007. Special provisions detailing the construction requirements for the proposed test sections were developed and incorporated in the construction contract documents.

The design cross section of the mainline pavement structure, as shown in Figure 4-1, consists of a 12-in. (305-mm) thick PCC surface resting on a 3-in. (76-mm) HMA base and 12-in. (305-mm) dense aggregate subbase. The outside lane, which was chosen as the location for the test sections, is 13 ft (4 m) wide (the center and inside lanes are each 12 ft [3.7 m] wide). PCC transverse joints are spaced 15 ft (4.6 m) and include 1.5-in. (38-mm) diameter dowel bars spaced 12 in. (305 mm) apart. Longitudinal joints are tied with #6 (0.75-in. [19-mm] diameter) tie bars spaced at 12 in. (305 mm).

Construction of New Test Sections

Mainline PCC paving consisted of two separate slipform paving runs. In the first run, the 12-ft (3.7-m) wide center and 13-ft (4.0-m) wide outside lanes were paved monolithically in each direction. In the second run, the 12-ft (3.7-m) inside lane was paved in each direction, with tie-in to the center lane slab.

Placement of the 3-in. (76-mm) HMA base on the dense aggregate subbase typically preceded the paving work of the first paving run by 2 to 3 days. Also, a paving gap of about 125 ft (38 m) for both directions was required at the toll plaza due to the structural work that took place on both sides of the

Table 4-1. Features of the selected texturing types.

Texture No.	Pre-Texture/ Secondary Texture	Primary Texture				
		Texture	Direction	Spacing, in. (mm)	Depth, in. (mm)	Other
1	Heavy Turf Drag (MTD ≥ 0.04 in. [1mm], Minnesota Astroturf)					
2	None	Tining	Longitudinal	0.75 (19)	0.125 (3.2)	-
3	None	Diamond Grinding	Longitudinal	0.11 (2.8)	-	Without jacks
4	Turf Drag	Tining	Longitudinal Meander	0.75 (19)	0.125 (3.2)	Sinusoidal Wave[a]
5	Turf Drag	Tining	Longitudinal	0.75 (19)	0.125 (3.2)	-
6	Turf Drag	Tining	Longitudinal	0.75 (19)	<0.1 (<2.5)	Shallow Tining
7	Burlap Drag	Grooving	Longitudinal	0.75 (19)	0.25 (6.4)	-
8	Turf Drag	Grooving	Longitudinal	0.75 (19)	0.25 (6.4)	-
9	Burlap Drag	Tining	Transverse	0.5 (12.7)	0.125 (3.2)	Georgia 0.5-in. (12.7-mm) spacing
10[b]	Burlap Drag	Tining	Transverse[c]	Variable	0.125 (3.2)	-
11[c]	Participating Agency Standard					

[a] Sinusoidal wave with wavelength of 16 ± 2 in. (406 ± 50 mm) and amplitude of 8 ± 2 in. (203 ± 50 mm).
[b] Control sections for reference.
[c] Skewed or nonskewed, depending on joint orientation.

roadway. The paving and texturing equipment used in the first paving run (center and outside lanes) were as follows:

- Concrete Paver—25-ft (7.6-m) wide monolithic slipform paver, equipped with spreader, dowel bar inserter (DBI), and tie-bar inserter (TBI);
- Pavement Surface Texturing Machine—25-ft (7.6-m) wide with front-mount turf/burlap drag, center-mount transverse or longitudinal tining carriage, and rear-mount curing compound applicator.

For the first paving run, the concrete was hauled in on semi-trailer dump trucks and concrete transport trucks and dumped on the 3-in. (76-mm) HMA base in front of the paver. The PCC was spread, consolidated, and screeded by the paver, and automatically fitted with dowel bars (every 15 ft [4.6 m]) and tie bars (inside edge of center slab and at interface of center and outside slabs). The surface was then manually floated and edged prior to the prescribed texturing (pretexture and/or tine) and curing application, which was completed using the texturing machine.

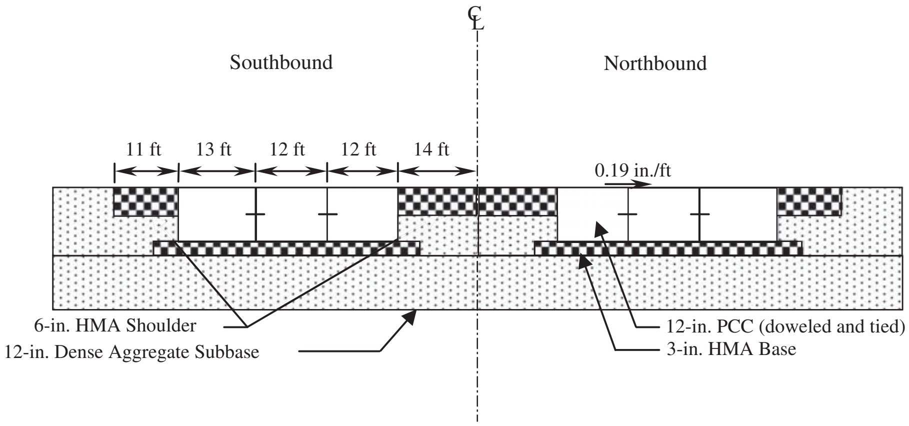


Figure 4-1. Pavement cross-section.

Table 4-2 lists the surface textures that were constructed and notes the deviations from the originally planned textures. As noted, the following modifications were made:

- Addition of a second heavy turf drag section (Texture 1b).
- Elimination of the longitudinal meander tine (Texture 4) because of its very high construction cost.
- Addition of a longitudinal tine with heavy turf drag pretexture (Texture 5b).
- Inclusion of a second texture (skewed variable tine) (Texture 12).

In general, each day of paving associated with the first paving run (center and outside lanes) involved a different surface texture. Figure 4-2 shows the sequence of paving for the first paving run, the beginning and ending locations (in stations) of each day's paving, and the texturing applied as part of the study. Only the specified pre-texture for Textures #3, #7, and #8 was applied at the time of paving; the associated grinding/grooving was performed several weeks later.

Paving and fresh concrete texturing activities were closely monitored and documented. Tire tread depth gauge measurements of the various tinings were taken behind the tining machine to check accuracy of groove dimensions (i.e., spacing and depth). Sand patch tests were conducted on heavy turf drag sections within 2 days after placement to check the mean texture depth (MTD) requirement. Table 4-3 provides additional information on each day's paving, including the weather conditions and description of the texturing activities. Figures 4-3 through 4-11 illustrate the paving operations and resulting surface textures.

Diamond Grinding and Grooving

As indicated in Table 4-3, all of the formed or fresh concrete textures (e.g., deep turf drag, longitudinal tining, and transverse tining) at the test site were completed between April 30 and May 25, 2007. The three cut or hardened concrete textures were constructed several weeks later (September 29 through October 6, 2007), following the completion of paved shoulders on which the grinding/grooving equipment could operate. Weather conditions during the grooving and grinding operations were fairly seasonal, with daily highs in the upper 70s to lower 80s and only a trace of precipitation on one day. Grinding and grooving was performed full-width over the center and outside lanes. The diamond grinding equipment and

Table 4-2. Constructed textures.

TEXTURE NO.	TEXTURE		COMMENTS
	Primary (spacing × depth)	Secondary	
1a	None	Heavy Turf Drag (MTD 0.015 – 0.03 in. (0.4 – 0.75 mm)	
1b	None	Heavy Turf Drag (MTD 0.025 – 0.04 in. (0.6 - 1.1 mm)	Section 1b added due to inadequate levels of MTD in Section 1a
2	Long Tine—0.75 in. × 0.13 in. (19 mm × 3.2 mm)	None	
3	Long Diamond Grind—0.11 in. (2.8 mm) (without jacks)	None	
4	Long Meander Tine—0.75 in. × 0.13 in. (19 mm × 3.2 mm)	Std Turf Drag	Not installed due to high cost.
5a	Long Tine—0.75 in. × 0.13 in. (19 mm × 3.2 mm)	Std Turf Drag	
5b	Long Tine—0.75 in. × 0.13 in. (19 mm × 3.2 mm)	Heavy Turf Drag	Section 5b added to examine effects of heavy turf drag pretexture
6	Shallow Long Tine—0.75 in. × <0.1 in. (19 mm × <2.5 mm)	Std Turf Drag	
7	Long Groove—0.75 in. × 0.25 in. (19 mm × 6.4 mm)	Burlap Drag	
8	Long Groove—0.75 in. × 0.25 in. (19 mm × 6.4 mm)	Std Turf Drag	
9	GA 0.5-in. Tran Tine—0.5 in. × 0.13 in. (12 mm × 3.2 mm)	Burlap Drag	
10	Variable Tran Tine—variable* × 0.13 in. (3.2 mm)	Burlap Drag	
11	Tran Tine—1 in. × 0.13 in. (25.4 mm × 3.2 mm) (ISHTA "Old" Std)	Burlap Drag	
12	Skewed Variable Tine—variable** × 0.13 in. (3.2 mm) (ISHTA "New" Std)	Std Turf Drag	Section 12 added to evaluate Illinois Tollway's new texturing standard

* Spacing varies from 0.38 to 0.81 in. (10 to 21 mm), with average spacing of 0.5 in. (12.7 mm).
** Spacing varies from 0.67 to 2.13 in. (17 to 54 mm), with average spacing of 1.46 in. (37.1 mm).

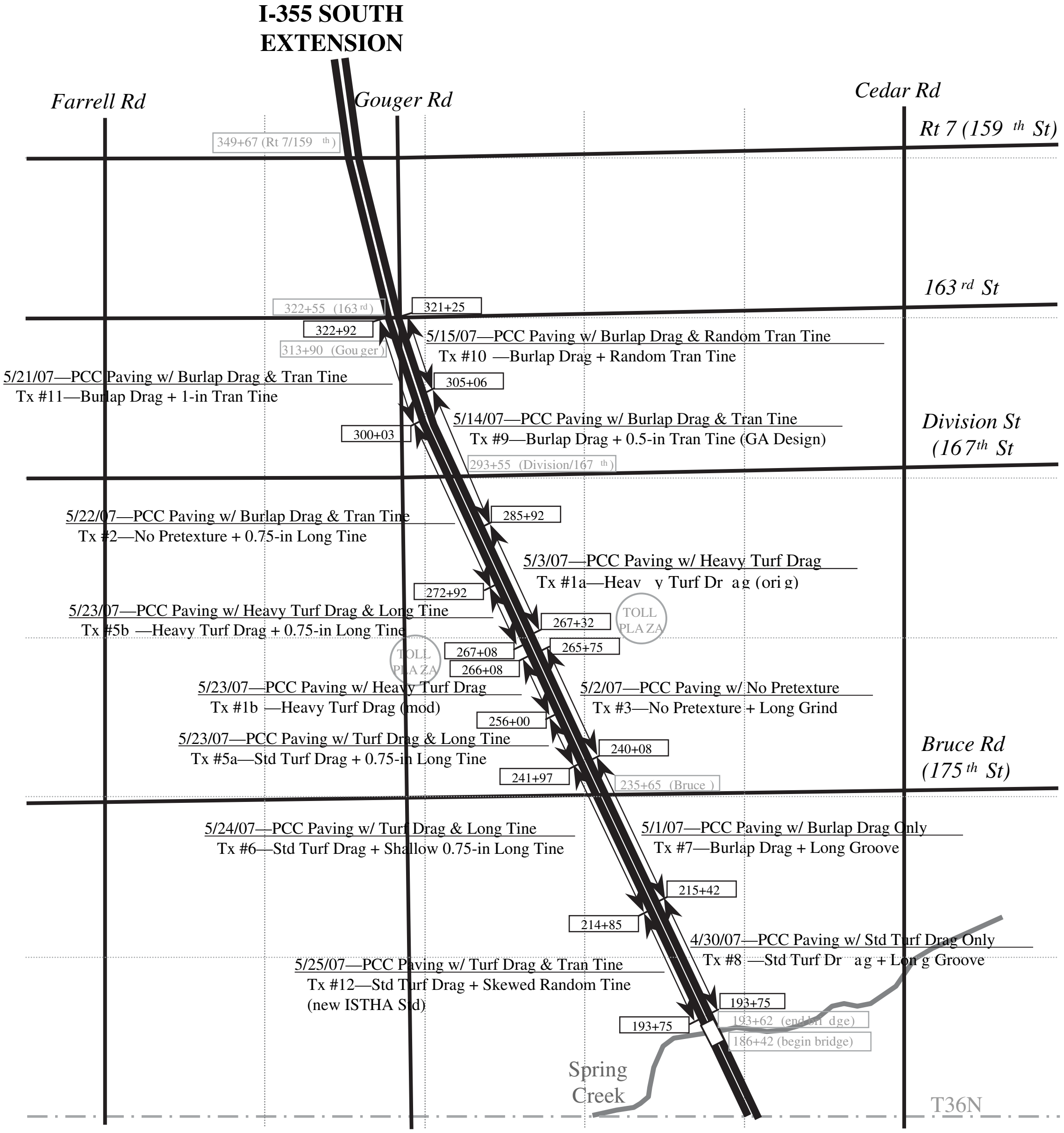


Figure 4-2. Concrete paving and texturing sequence.

the resulting texture are shown in Figures 4-12 through 4-14. The diamond groove textures were created using a bridge deck groover, equipped with a 30-in. (762-mm) diamond-blade cutting head. Figures 4-15 through 4-17 show the grinding equipment and produced texture.

Establishing Test Segments

Figure 4-18 shows the location of the test sections on the site. Most test segments were 528 ft (161 m) long. Locations of the segments were chosen to provide a good representation of the specified texture and to keep clear of roadway features that could affect friction, texture, and noise measurements (e.g., overpasses, overhead sign structures, embankments, locations that were diamond ground to remove bumps or excessive roughness).

Collection of Concrete Data

Concrete mixture design and materials/construction quality data of the pavement were obtained from the project QA/QC testing contractor. These data included the following:

- Mixture Design
  - Aggregate type/source, properties.
  - Cement content/water-to-cement ratio.
  - Slump.
  - Gradation.
  - Compressive strength.

Table 4-3. Details of concrete paving activities on South Extension.

Texture No. and Description	Location, Station/Direction	Date and Time of Paving	Weather Conditions	Description of Texturing Operations
1a—Heavy Turf Drag (orig)	267+92 to 285+92 NB	5/3/07, 6:00 am - 4:00 pm	Clear and Sunny, Light to Moderate Winds (50 - 70°F)	• Turf drag pretexture created using 24-ft wide by 4-ft long polyethylene turf mat weighted down with 22-ft long 2×10 lumber. • 1 pass—combined turf drag and curing compound spray (distance maintained behind paver = 50 to 125 ft).
1b—Heavy Turf Drag (mod)	266+08 to 256+00 SB	5/23/07, 6:00 am - 5:00 pm	Clear and Sunny Light Winds (am), Moderate Winds (pm) (58 - 88°F)	• Turf drag pretexture created using 24-ft wide by 4-ft long polyethylene turf mat weighted down with 22-ft long 2×10 <u>and</u> 22-ft long 2×6 lumber. • 1 pass—combined turf drag and curing compound spray (distance maintained behind paver = 50 to 125 ft).
2—No Pretexture + 0.75-in. Long Tine	300+03 to 272+92 SB	5/22/07, 6:00 am - 7:00 pm	Clear and Sunny, Light to Moderate Winds (56 - 86°F)	• No pretexture applied; longitudinal tining created using tines uniformly spaced 0.75 in. (19 mm) apart. • 2 passes—first pass for longitudinal tining, second pass for curing compound spray (distance maintained behind paver = 50 to 125 ft).
3—No Pretexture + Long Grind	240+08 to 265+75 NB	5/2/07, 6:00 am - 5:30 pm	Partly Cloudy, Moderate Winds (50 - 72°F)	• No pretexture applied; surface just floated and edged, and sprayed with curing compound.
5a—Std Turf Drag + 0.75-in. Long Tine	256+00 to 241+97 SB	5/23/07, 6:00 am - 5:00 pm	Clear and Sunny Light Winds (am), Moderate Winds (pm) (58 - 88°F)	• Turf drag pretexture and longitudinal tining created using (a) 24-ft wide by 4-ft long polyethylene turf mat (unweighted) and (b) longitudinal tines uniformly spaced 0.75 in. (19 mm) apart. • 2 passes—first pass for combined turf drag and longitudinal tining, second pass for curing compound spray (distance maintained behind paver = 75 to 100 ft).
5b—Heavy Turf Drag + 0.75-in. Long Tine	272+92 to 267+08 SB	5/23/07, 6:00 am - 5:00 pm	Clear and Sunny Light Winds (am), Moderate Winds (pm) (58 - 88°F)	• Turf drag pretexture and longitudinal tining created using (a) 24-ft wide by 4-ft long polyethylene turf mat weighted down with 22-ft long 2×10 lumber and (b) longitudinal tines uniformly spaced 0.75 in. (19 mm) apart. • 2 passes—first pass for combined turf drag and longitudinal tining, second pass for curing compound spray (distance maintained behind paver = 75 to 100 ft).
6—Std Turf Drag + 0.75-in. Shallow Long Tine	241+97 to 214+85 SB	5/24/07, 6:30 am - 5:30 pm	Clear and Sunny, Moderate to Strong Winds (65 - 89°F)	• Turf drag pretexture and longitudinal tining created using (a) 24-ft wide by 4-ft long polyethylene turf mat (unweighted) and (b) longitudinal tines uniformly spaced 0.75 in. (19 mm) apart. • 2 passes—first pass for combined turf drag and longitudinal tining, second pass for curing compound spray (distance maintained behind paver = 75 to 100 ft).

(continued on next page)

Table 4-3. (Continued).

Texture No. and Description	Location, Station/Direction	Date and Time of Paving	Weather Conditions	Description of Texturing Operations
7—Burlap Drag + Long Groove	215+42 to 240+08 NB	5/1/07, 6:00 am - 7:00 pm	Partly Cloudy, Moderate Winds (56 - 78°F)	• Burlap drag pretexture created using 24-ft wide by 4-ft long burlap section. • 1 pass—combined burlap drag and curing compound spray (distance maintained behind paver = 50 to 125 ft).
8—Std Turf Drag + Long Groove	193+75 to 215+42 NB	4/30/07, 6:00 am - 7:00 pm	Clear and Sunny, Light Winds (52 - 75°F)	• Turf drag pretexture created using 24-ft wide by 4-ft long polyethylene turf mat (unweighted). • 1 pass—combined turf drag and curing compound spray (distance maintained behind paver = 50 to 125 ft).
9—Burlap Drag + 0.5-in. Tran Tine (GA design)	285+92 to 305+06 NB	5/14/07, 6:00 am - 5:30 pm	Clear and Sunny, Light to Moderate Winds (54 - 90°F)	• Burlap drag pretexture and transverse tining created using (a) 24-ft wide by 4-ft long burlap section and (b) transverse tines uniformly spaced 0.5 in. (13 mm) apart. • 2 passes—first pass for combined burlap drag and transverse tining, second pass for curing compound spray (distance maintained behind paver = 75 to 100 ft).
10—Burlap Drag + Variable Tran Tine	305+06 to 321+25 NB	5/15/07, 6:00 am - 3:30 pm	Clear and Sunny (am), Light Showers (pm) Light to Moderate Winds (58 - 79°F)	• Burlap drag pretexture and transverse tining created using (a) 24-ft wide by 4-ft long burlap section and (b) transverse tines spaced according to dimensions given in Table B-1 in Appendix B (available on line). • 2 passes—first pass for combined burlap drag and transverse tining, second pass for curing compound spray (distance maintained behind paver = 75 to 100 ft).
11—Burlap Drag + 1-in. Tran Tine (ISTHA Std)	322+92 to 300+03 SB	5/21/07, 6:00 am - 6:00 pm	Clear and Sunny, Light Winds (45 - 83°F)	• Burlap drag pretexture and transverse tining created using (a) 24-ft wide by 4-ft long burlap section and (b) transverse tines uniformly spaced 1.0 in. (25 mm) apart. • 2 passes—first pass for combined burlap drag and transverse tining, second pass for curing compound spray (distance maintained behind paver = 75 to 100 ft).
12—Std Turf Drag + Skewed Variable Tine	214+85 to 193+75 SB	5/25/07, 7:00 am - 6:00 pm	Partly Cloudy, Light Winds (56 - 72°F)	• Turf drag pretexture and transverse tining created using (a) 24-ft wide by 4-ft long polyethylene turf mat (unweighted) and (b) transverse tines spaced according to dimensions given in Table B-2 in Appendix B (available on line). • 2 passes—first pass for combined turf drag and skewed transverse tining, second pass for curing compound spray (distance maintained behind paver = 75 to 100 ft).

Note: Wind speed classification according to Beaufort wind speed scale (Light = 1-10 mi/hr, Moderate = 10-22 mi/hr, Strong = 22-33 mi/hr)
1 in. = 25.4 mm; 1 ft = 0.305 m; 1 mi = 1.61 km; °C = 5/9×(°F–32)
ISTHA=Illinois State Toll Highway Authority

Figure 4-3. PCC paving.

Figure 4-4. Longitudinal tining.

Figure 4-5. Longitudinally tined surface.

Figure 4-6. Heavy turf drag texturing.

Figure 4-7. Heavy turf drag finish (Section 1b).

Figure 4-8. 0.5-in (12.7-mm) transverse tining (Section 9).

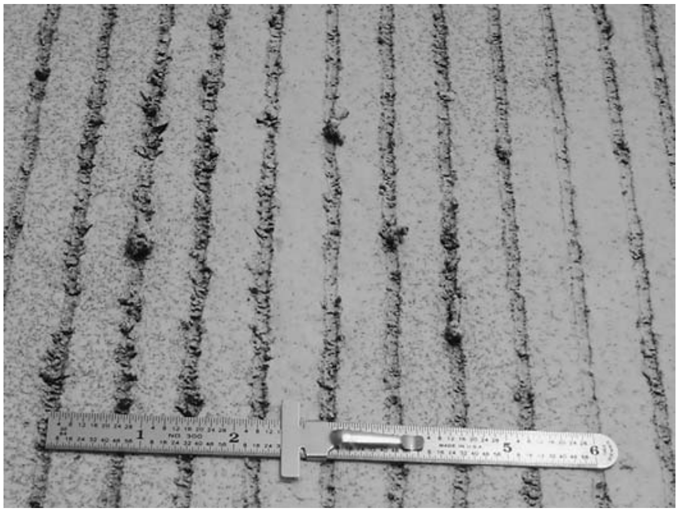


Figure 4-9. Shallow longitudinal tine (Section 6).

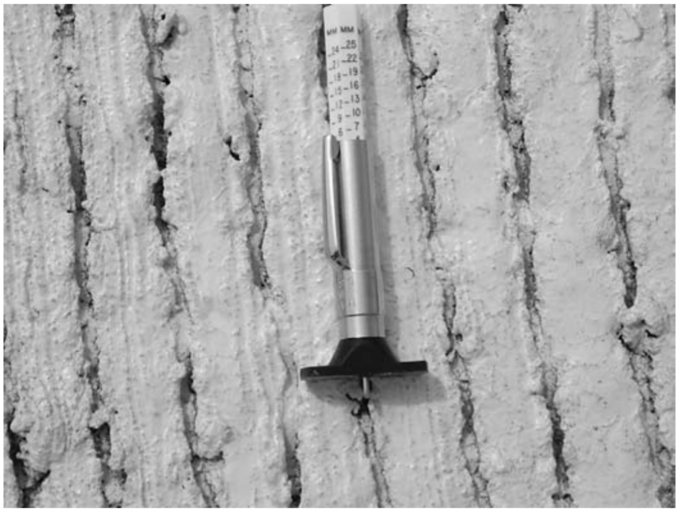


Figure 4-10. Longitudinal tine with heavy turf drag pretexture (Section 5b).

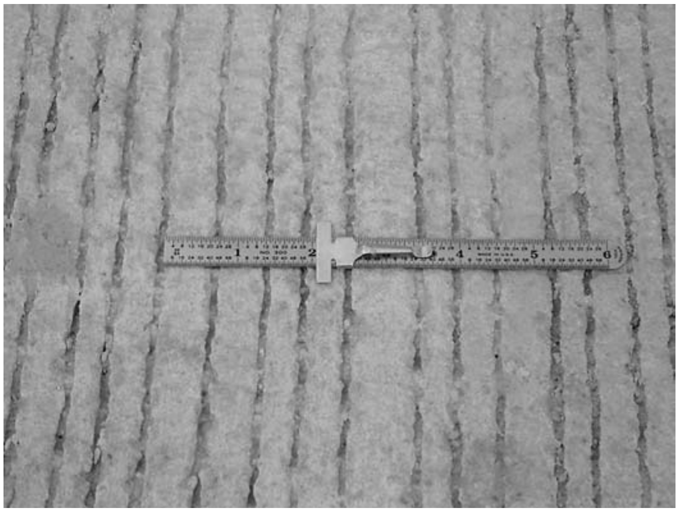


Figure 4-11. Variable transverse tine (Section 10).

Figure 4-12. Diamond grinding machine.

Figure 4-13. Diamond-ground surface (Section 3).

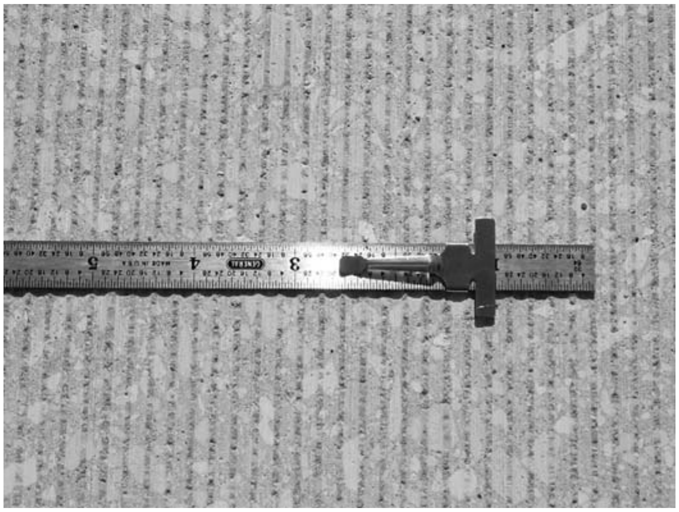


Figure 4-14. Close-up picture of diamond-ground surface (Section 3).

Figure 4-15. Longitudinal grooving machine.

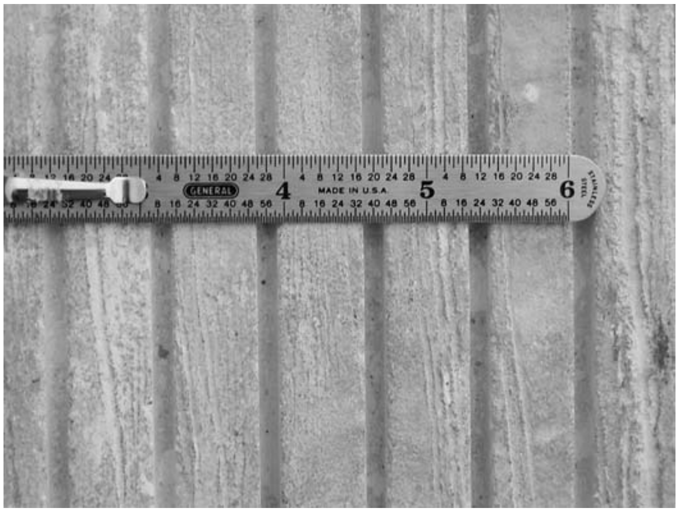


Figure 4-17. Close-up picture of longitudinal grooving (Section 7).

- Materials/Construction Quality
  - Water-to-cement ratio.
  - Slump.
  - Air content.
  - Air and mix temperatures.
  - Compressive strength (3- and 14-day).
  - Initial smoothness (profilograph traces and zero blanking-band profile index [PI0.0] values for 0.1-mi [0.16-km] segments before and after grinding).

Texture, Friction, and Noise Test Procedures

Field Testing Protocol

Measurement of texture, friction, and noise of the newly constructed sections was obtained using the same tests (and corresponding outputs) performed on the existing texture test sections. These included texture measurements with the CT Meter (ASTM E 2157) and the high-speed texture profiler, friction measurements with the DF Tester (ASTM E 1911) and the locked-wheel tester (ASTM E 274), and measurements for near-field SI noise, interior vehicle noise, and far-field CPB noise.

Figure 4-16. Longitudinal grooved center lane (Section 7).

CT Meter and DF Tester testing were performed at two different time periods: the first during the week of July 23, 2007, and the second during the week of October 7, 2007. In general, the same testing protocols were followed, with repeat tests conducted in both the right wheelpath (24 in. [610 mm] from lane edge) and lane center (72 in. [1,830 mm] from lane edge) of the test segment established within each test section. Although test segments on the South Extension were about half of the length of the segments representing existing textures (528 ft versus 1,056 ft [161 m versus 322 m]), the same number of CT Meter and DF Tester tests were performed—15 each in the right wheelpath and lane center along the length of each test segment.

Noise and high-speed texture were tested at various times between late July and early October, 2007. SI data were collected in accordance with AASHTO Provisional Standard TP076-08 (in draft form), which included a vertical dual probe configuration with the new ASTM Standard Reference Test Tire (SRTT) (see Figures 4-19 and 4-20). At least three test runs were made with the pairs of microphones simultaneously collecting front and rear SI data. The average of the front- and rear-measured SI values was then computed.

Prior to formal SI testing, a comparison was made of the dual-probe/SRTT test method and the single-probe/Aquatred III method. Multiple test runs were made with each setup on two different test sections. The overall average difference in SI measurements was insignificant (0.1 dB(A)), thus no

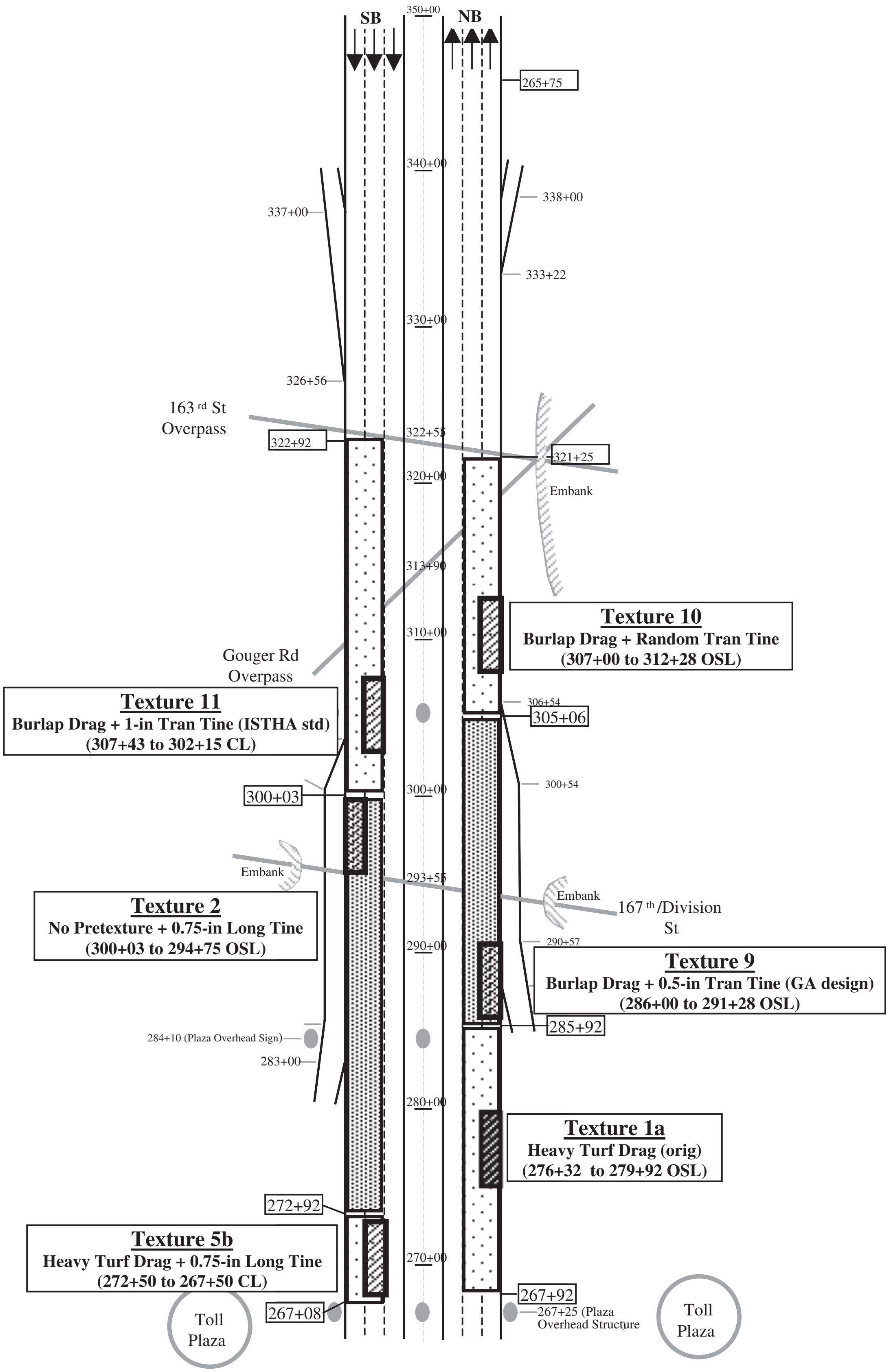


Figure 4-18a. Location of test sections on the test site north end.

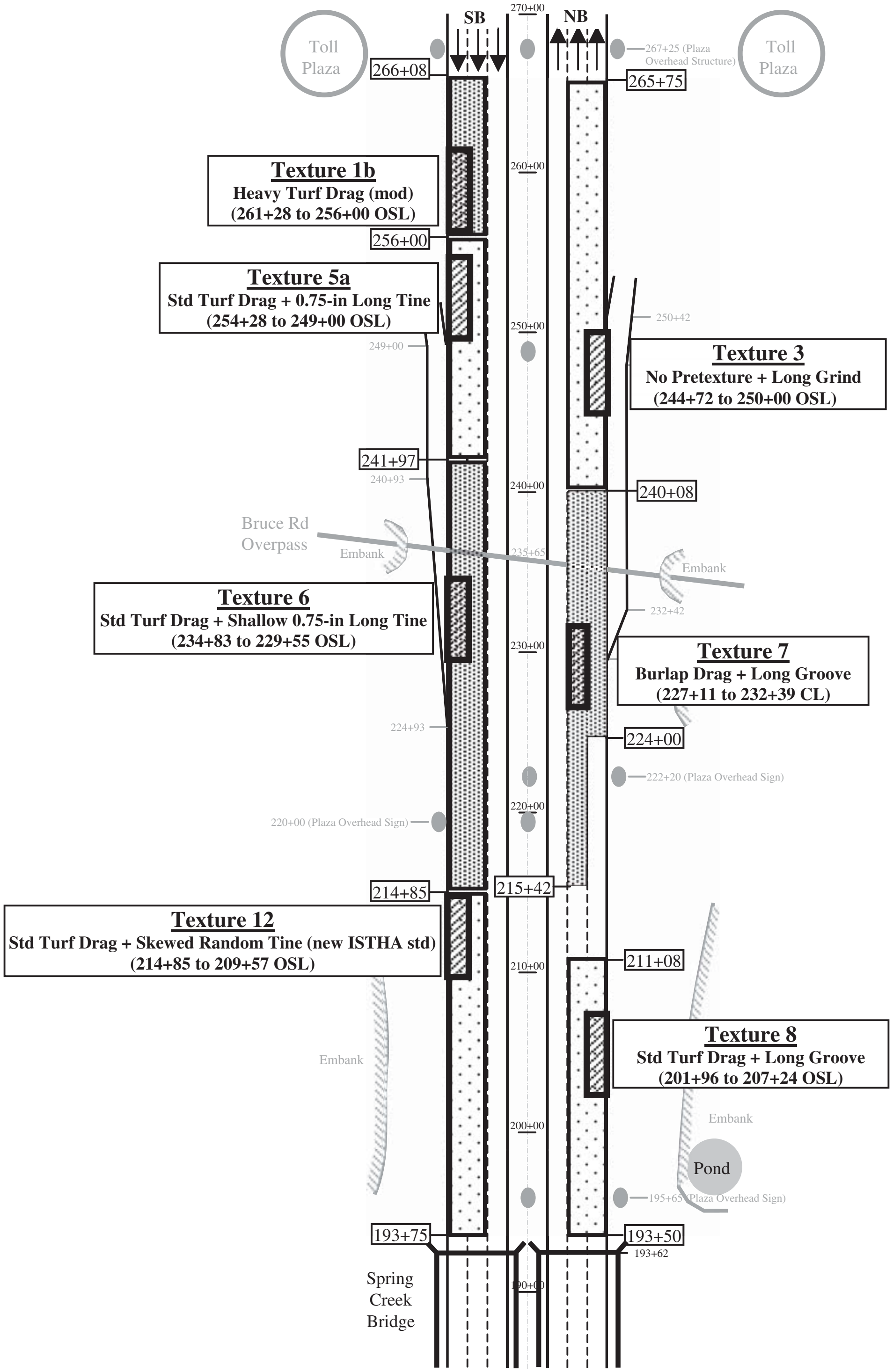


Figure 4-18b. Location of test sections on the test site south end.

Figure 4-19. SI vertical dual-probe configuration.

adjustments were made and formal testing commenced. The dual-probe/SRTT test method reduced by half the number of runs required to average the front and rear SI measurements and increased mechanical reliability. In addition, the reduced vibration of the probe bracket resulted in less variability in the data.

In the case of far-field CPB tests, the setup was placed at 300 ft (91.5 m) from the start instead of 508 ft (155 m). Also, because the outside shoulders were largely incomplete during testing, it was decided that CPB measurements would be obtained by setting up the noise equipment on the inside shoulder and driving the test segment with the Aquatred III tires mounted on the left side of the vehicle closest to the microphone. Thus the 25-ft (7.6-m) offset distance prescribed in the pass-by test was maintained and no correlation was needed for differing tire types, since the Aquatred tire was used for the existing test sections and the new Tollway sections. In addition, to eliminate background noise, CPB testing was conducted during periods when there was no construction traffic, usually after the end of the work shift or on weekends.

Figure 4-20. ASTM SRTT and Goodyear Aquatred III test tire.

Locked-wheel friction testing was also performed at two different times: in early September and in mid October. In the first round of testing, both ribbed (ASTM E 501) and smooth (ASTM E 524) test tires were used, with three tests performed per tire at both the lane center and the right wheelpath. In the second round of testing, only ribbed tire testing of the lane center and right wheelpath was performed.

Texture, Friction, and Noise Test Results

This section summarizes the results of the texture, friction, and noise tests conducted on the test sections. The results are provided in terms of the key outputs from the various tests and other extrapolated indices.

Table 4-4 lists the mean texture values for each test section, based on measurements from both the right wheelpath and the lane center, the mean micro-texture and friction values measured for each section, and the mean noise levels, as measured at the pavement–tire interface, in the vehicle interior, and at the side of the road. (Detailed results are presented in Appendix D.)

Table 4-4. Texture, friction, and noise test data.

Sect No.	Texture Description	High-speed Profiler[1]		CT Meter[1]			DF Tester[1]		Locked-Wheel[1]		SI NOISE, DB(A)[1]	INT NOISE, DB(A)[1]	CPB NOISE, DB(A)
		MPD, mm	EMTD, mm	MPD, mm	MTD, mm	TR	DFT(20)[2]	F(60)[2]	FN40S/FN40R	F(60)[3]			
1a	Long Heavy Turf Drag[4]	0.40	0.52	N/A	N/A	N/ A	45.6	23.1	------ / 45.4	------ / 31.8	101.55	69.50	#N/A
1b	Long Heavy Turf Drag (mod)[4]	0.32	0.46	0.28	0.36	1.96	32.7	19.9	24.1 / 48.5	24.7 / 30.8	101.79	69.10	79.3
2	Long Tine (0.75-in. spacing, 0.125-in. depth), no pretexture	0.71	0.75	0.60	0.66	1.10	36.0	23.9	33.2 / 46.3	32.1 / 29.8	103.23	69.50	79.5
3	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers)	0.35	0.48	0.65	0.71	2.41	48.3	22.8	------ / 53.1	------ / 34.1	100.48	67.60	77.5
5a	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	0.55	0.65	0.51	0.58	1.19	33. 3	21.1	35.0 / 48.7	37.8 / 32.7	102.35	71.10	77.6
5b	Long Tine (0.75-in. spacing, 0.125-in. depth), heavy turf drag	1.22	1.20	1.02	1.06	1.25	42.9	30.8	44.2 / 47.5	41.8 / 31.8	105.31	72.00	82.4
6	Long Tine (0.75-in. spacing, 0.075-in. depth), turf drag	0.54	0.63	0.49	0.56	1.23	34. 1	21.2	34.0 / 45.9	34.1 / 31.7	102.20	68.40	78.7
7	Long Groove (0.75-in. spacing, 0.25-in. depth), burlap drag	1.04	1.05	1.02	1.06	0.74	44.8	30.5	------ / 46.8	------ / 30.4	101.69	68.10	79.1
8	Long Groove (0.75-in. spacing, 0.25-in. depth), turf drag	0.98	0.98	1.22	1.25	0.78	53.6	34.6	------ / 57.1	------ / 35.6	102.47	68.00	78.3
9	Tran Tine (0.5-in. spacing, 0.125-in. depth), burlap drag (GA design)	0.48	0.59	0.48	0.55	1.41	42.4	23.6	------ / 46.0	------ / 29.7	102.63	67.70	80.7
10	Tran Tine (variable spacing, 0.125-in. depth), burlap drag	0.62	0.70	0.62	0.68	1.36	36.8	23.4	37.3 / 60.0	36.9 / 40.5	102.85	68.80	81.2
11	Tran Tine (1.0-in. spacing, 0.125-in. depth), burlap drag (old ISTHA std)	0.50	0.60	0.44	0.51	1.10	34.3	20.9	35.1 / 49.6	31.8 / 32.1	104.07	69.30	80.3
12	Tran Skew Tine (variable spacing, 0.125-in. depth), turf drag (new ISTHA std)	0.64	0.71	0.58	0.65	1.28	36.9	23.5	------ / 45.4	------ / 31.8	102.69	67.80	80.1

[1] Mean values based on right wheelpath and lane center measurements.
[2] Values substantially lower than expected.
[3] Smooth-Tire Friction Number, unless otherwise noted.
[4] Sand patch tests conducted on heavy turf drag textures (after hardening of the PCC) yielded average MTD values of 0.023 in. (0.6 mm) for Sect 1a and 0.03 in. (0.76 mm) for Sect 1b.
NA=Not available

CHAPTER 5

Data Analysis

This chapter presents the analyses of the data obtained from the measurements on the test sections. These analyses were used to provide a basis for developing a process and detailed sample/guide specifications for selecting texture types.

The analyses recognized the limitations of the data (e.g., concrete and aggregate properties data) and focused on the texture wavelengths because of their reported influence on pavement friction and noise. As indicated previously, wavelengths fall primarily in the 2-in. (50-mm) and less range and are largely characterized as macro-texture and micro-texture.

Friction is highly dependent on the ranges of texture. Micro-texture contributes significantly to friction on dry roads at all speeds and to wet roads at slower speeds. Macro-texture significantly influences friction on wet roads at higher speeds. Therefore, the durability of friction is governed by the polish and abrasion properties of exposed aggregate and by the wear properties of the mix.

Noise is mostly a function of macro-texture and the lower wavelength levels of mega-texture. Other factors, such as pavement porosity and stiffness, have been reported to affect noise, but to a much lesser degree. Because the pavements tested in this study were all conventional, low-porosity pavements with similar stiffness levels, these factors were not considered in the analyses. Thus, the analysis of noise focused on the influence of macro- and lower mega-texture characteristics (e.g., texture depth, direction, orientation/bias, and spectrum parameters) and to some extent on the noise influence of wear properties of the concrete on durability.

Chapters 3 and 4 summarized the field testing results of existing and newly constructed test sections, respectively. These summaries represent the performance characteristics (quantifications of texture, friction, and noise levels) of different surface textures at a specific point in time. For a better understanding of the results and to apply them to the development of a texture selection process, the following detailed data analyses were conducted:

- Spectral Analyses
  - Noise Spectrum Analysis—Identification of undesirable tonal frequencies (high, medium, and low tones).
  - Power Spectral Density (PSD) Analysis of Texture—Fast Fourier Transform (FFT) to separate the wavelengths and amplitudes of the texture profiles into wavebands.
  - Texture and Noise Spectrum Comparisons—Cross comparisons of texture and noise spectra to identify texture wavelengths with significant bearings on noise frequencies.
- Comparative/Qualitative Analyses
  - Comparison of Textures by Site/Location—Direct/head-to-head comparisons of performance (initial and/or as a function of time/traffic) of textures at individual test sites/locations.
  - Texture Durability Analysis—Evaluation of micro-texture and macro-texture durability.
  - Noise Comparison of Textures—Comparison of noise characteristics by general texture categories and evaluation of effects of specific texture dimensions on noise.
  - Relationship of Near-Field Noise with Interior and Pass-By Noise.
- Statistical Analyses
  - Texture Depth Measurement Procedure—Correlation analysis of texture depth measured using a high-speed profiler and CT Meter.
  - Test Site/Location Performance Analysis—Analysis of variance (ANOVA) and Tukey groupings of texture performance (i.e., texture, friction, and noise) within individual test sites/locations.
  - National-Level Analysis of Texture, Friction, and Noise—ANOVA and regression analysis of texture, friction, noise, and site/location (i.e., traffic, climate, and selected pavement variables) data from all texture test sections.
  - Noise-Texture Relationship—Multiple regression analysis of texture parameter data (i.e., direction, depth, orientation, spectral parameters) and near-field SI noise data.

- Texture Construction Analysis—Analysis of the design/specified texture profile dimensions versus the actual/as-constructed texture dimensions.

Spectral Analyses

Noise Spectrum Analysis

Noise spectra were developed using software that utilizes Fourier transform to analyze the near-field SI noise data recorded over the full length of the individual test sections. Raw noise data were normalized for the ambient air temperature and barometric pressure from the time of testing and then post processed to create a 1/12th octave band spectrum, instead of the typical 1/3rd octave spectra, to provide better resolution for defining the test sections.

Figures 5-1 through 5-8 show the SI noise spectra of the existing test sections. The sections are presented in narrow-band 1/12th-octave spectrum to detect the presence of a tone or whine (highlighted by a prominent spike of ≥5 dB(A) difference from one octave to the next). Nearly all the spectra show a typical peak near 1,000 Hz followed by a low tonal apex at about 1,500 Hz. As seen in Figure 5-5 for the Iowa sections, the longitudinal-tined section (Section IA-1003) and the transverse-tined sections (Sections IA-1002, IA-8001, and IA-8002) show a definite high tonal spike near 1,500 Hz. Also, as Figure 5-8 shows, the transverse-tined section in Missouri (Section MO-1001) contains a medium spike near 2,000 Hz.

The 1/12th octave band spectra in Figure 5-9 shows a relatively close grouping among the newly constructed sections, with the exception of two transverse-tined sections (Sections 9 and 11). Section 11 (1-in. [25.4-mm] transverse tine) exhibited a significant tone at 1,000 Hz, which would be quite audible and contributes to the 104.2 dB(A) overall noise level. Section 9 (0.5-in. [12.7-mm] transverse tine) exhibited a predominant tone around 1,600 Hz and an overall noise level of 102.6 dB(A). With measured texture depths for these two sections being very similar, it can be seen that the closer tine spacing resulted in a higher-pitched and overall reduced noise level.

Figures 5-10 and 5-11 show SI noise spectra for the newly constructed longitudinal- and transverse-textured sections, respectively.

Texture Spectrum Analysis

The field testing results presented in Chapters 3 and 4 illustrate the effects of texture depth, direction, and orientation/bias on noise. However, texture wavelength properties also play a key role in the generation of noise. The wavelength properties are obtained through power spectral density (PSD) analysis that produces histograms of the contents or levels of texture observed for specific wavelength bands. Figure 5-12 illustrates the typical PSD function.

Sandberg and Ejsmont (2002) have suggested that to reduce exterior noise effectively, texture in the 0.80 to 24 in. (20 to

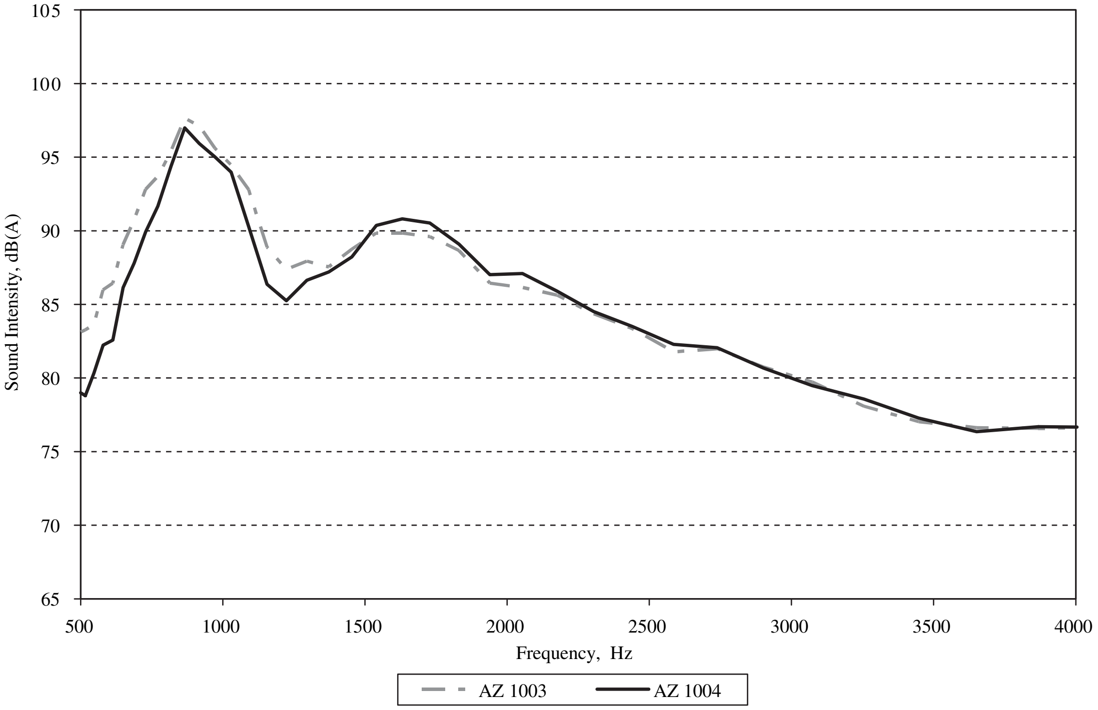


Figure 5-1. SI noise spectra for test sections in Arizona.

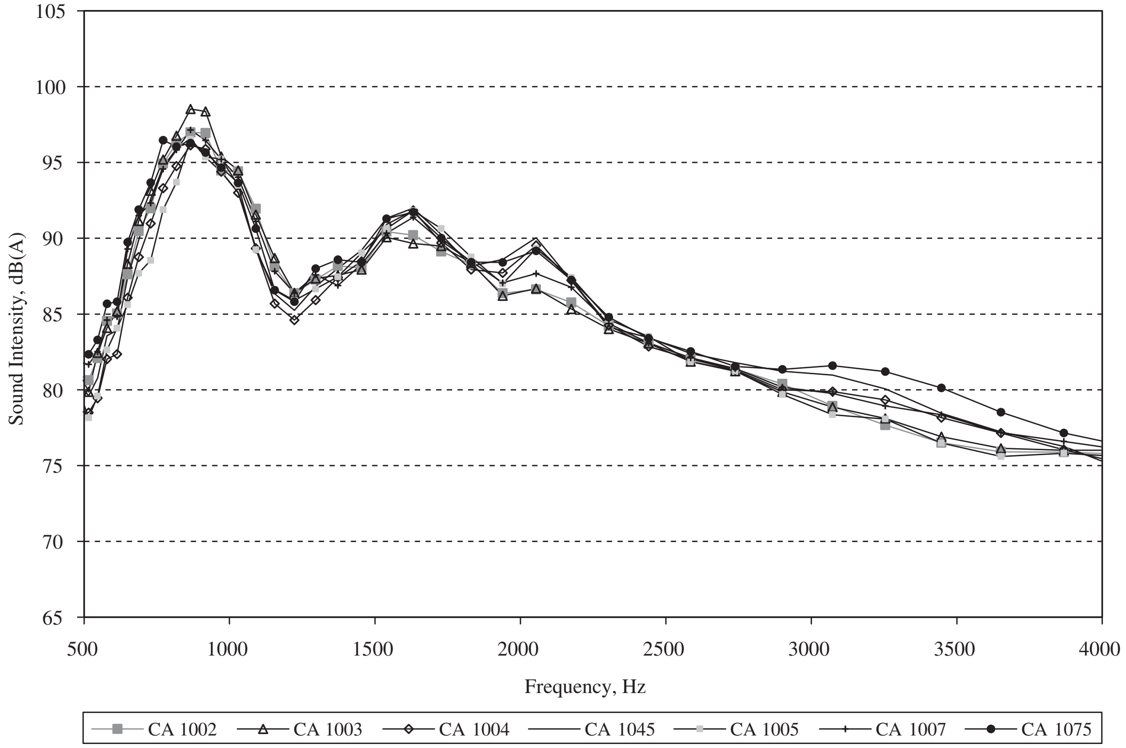


Figure 5-2. SI noise spectra for test sections in California.

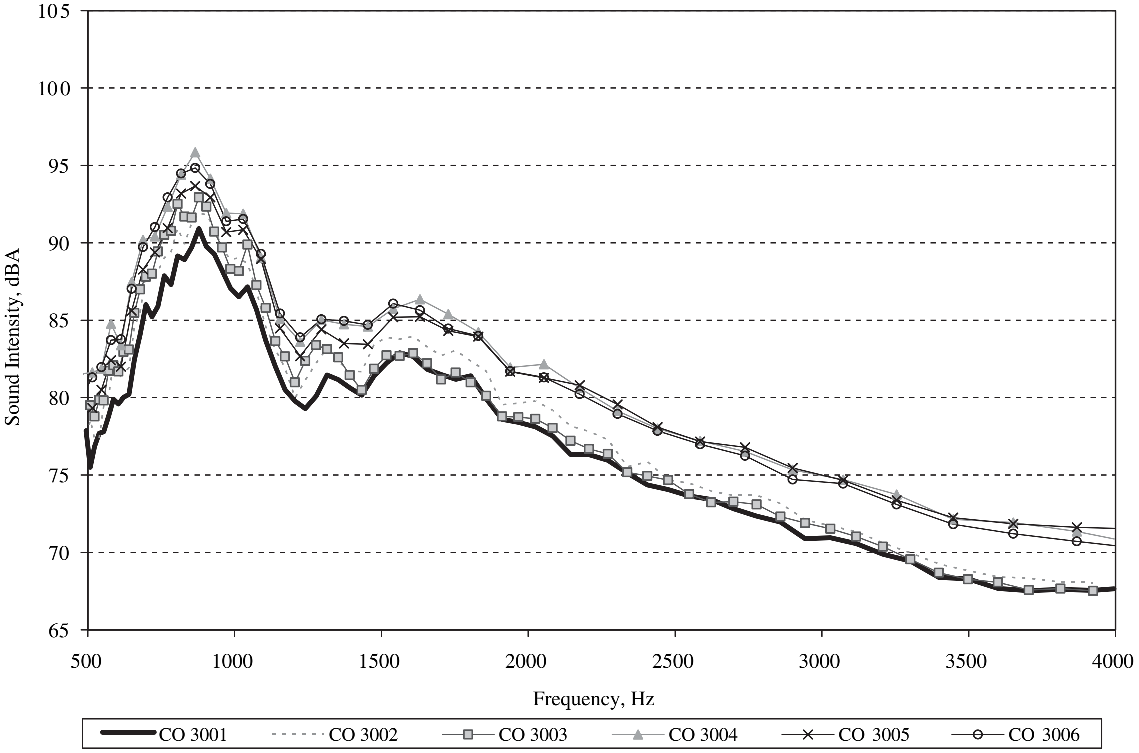


Figure 5-3. SI noise spectra for test sections in Colorado.

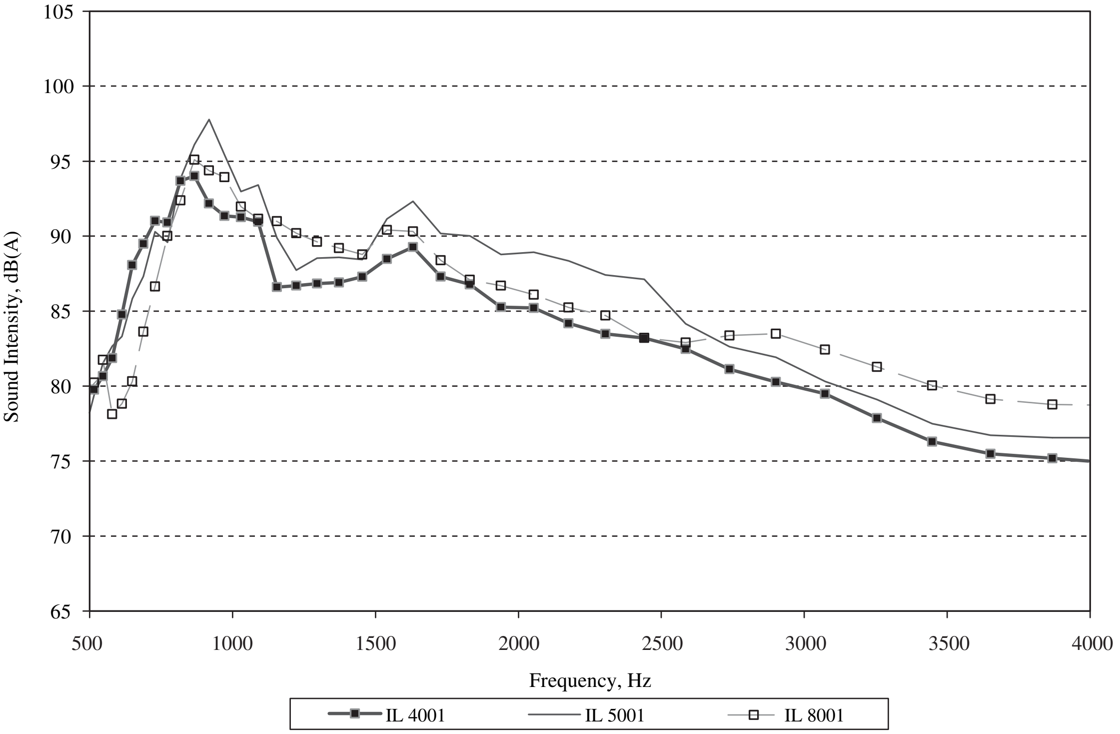


Figure 5-4. SI noise spectra for test sections in Illinois.

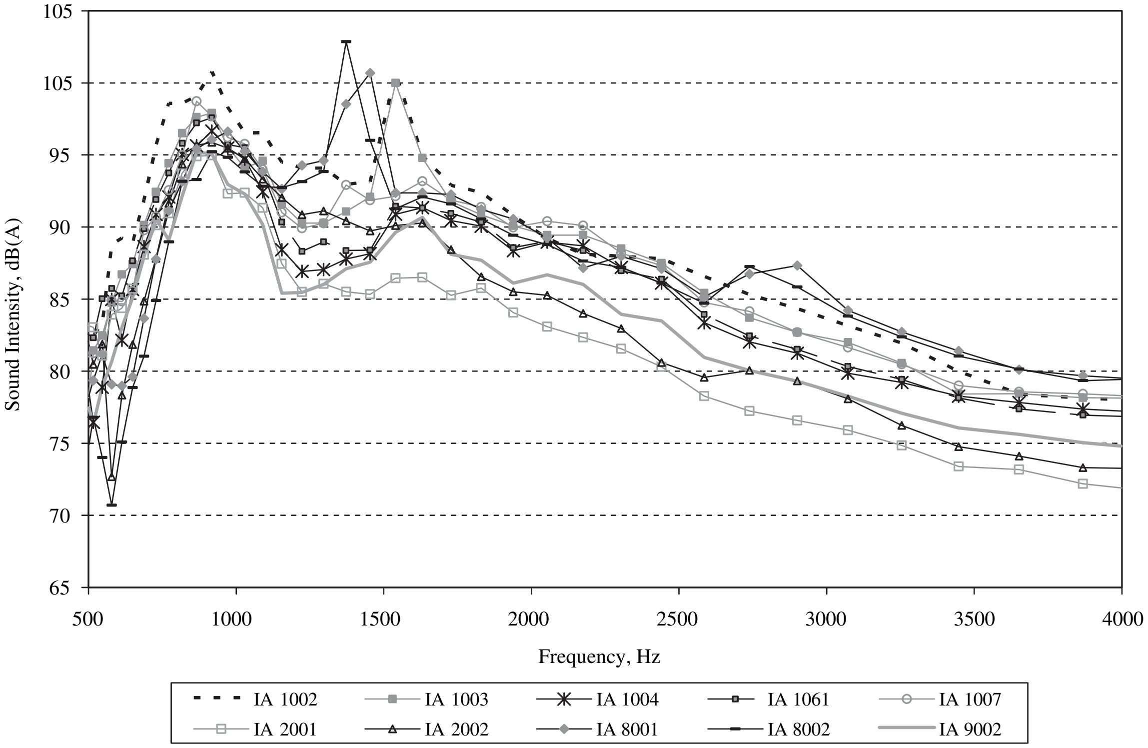


Figure 5-5. SI noise spectra for test sections in Iowa.

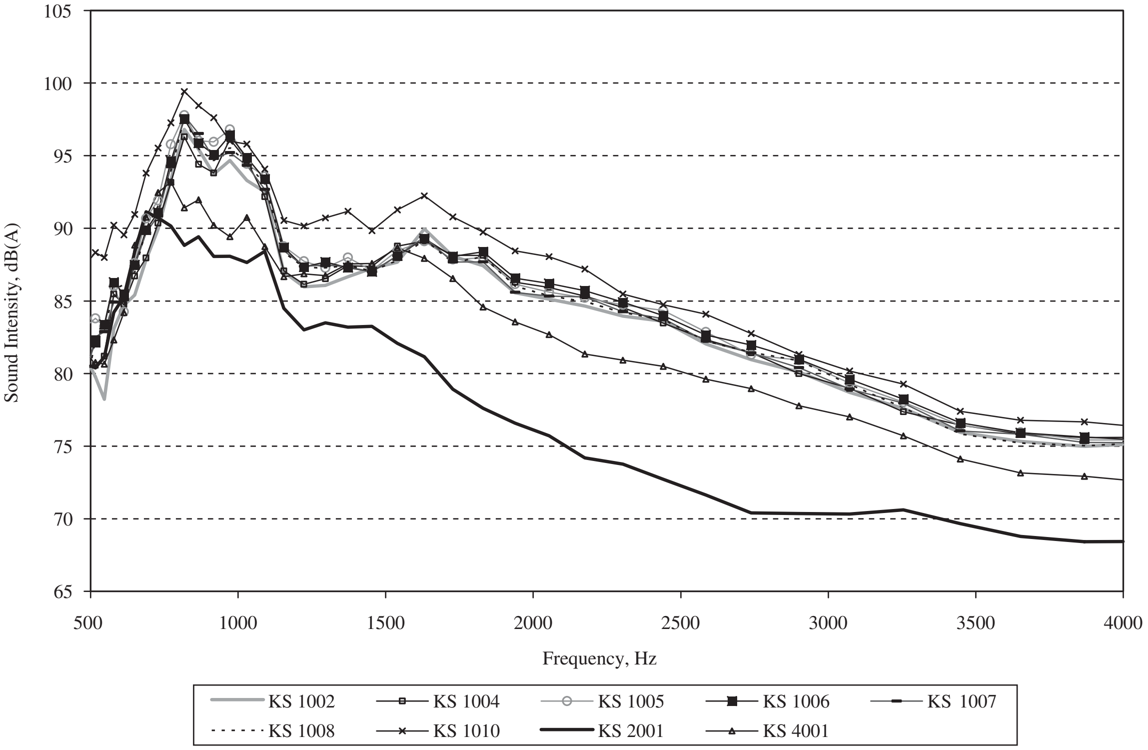


Figure 5-6. SI noise spectra for test sections in Kansas.

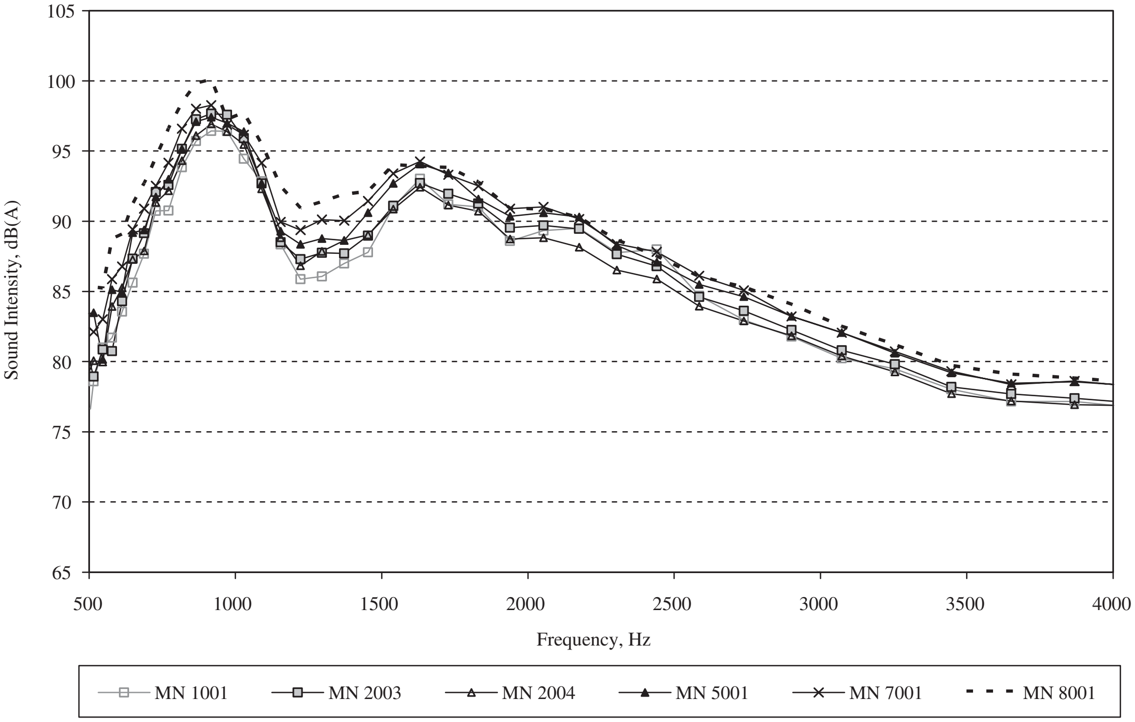


Figure 5-7. SI noise spectra for test sections in Minnesota.

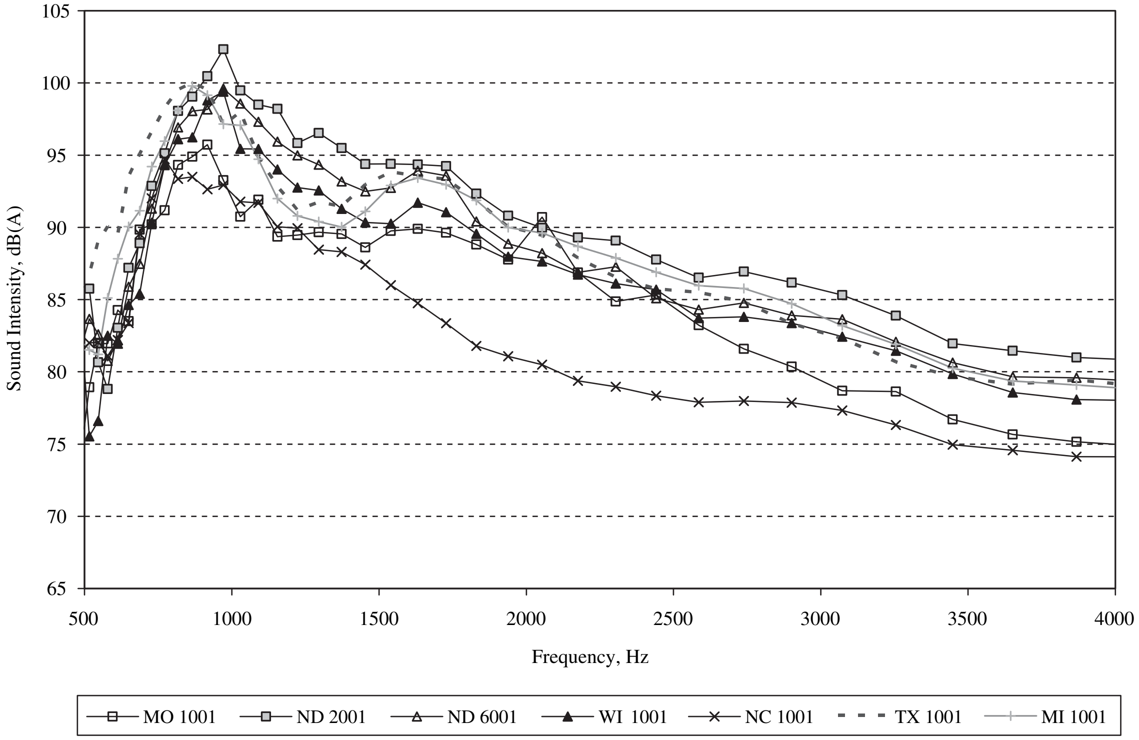


Figure 5-8. SI noise spectra for test sections in Michigan, Missouri, North Carolina, North Dakota, Texas, and Wisconsin.

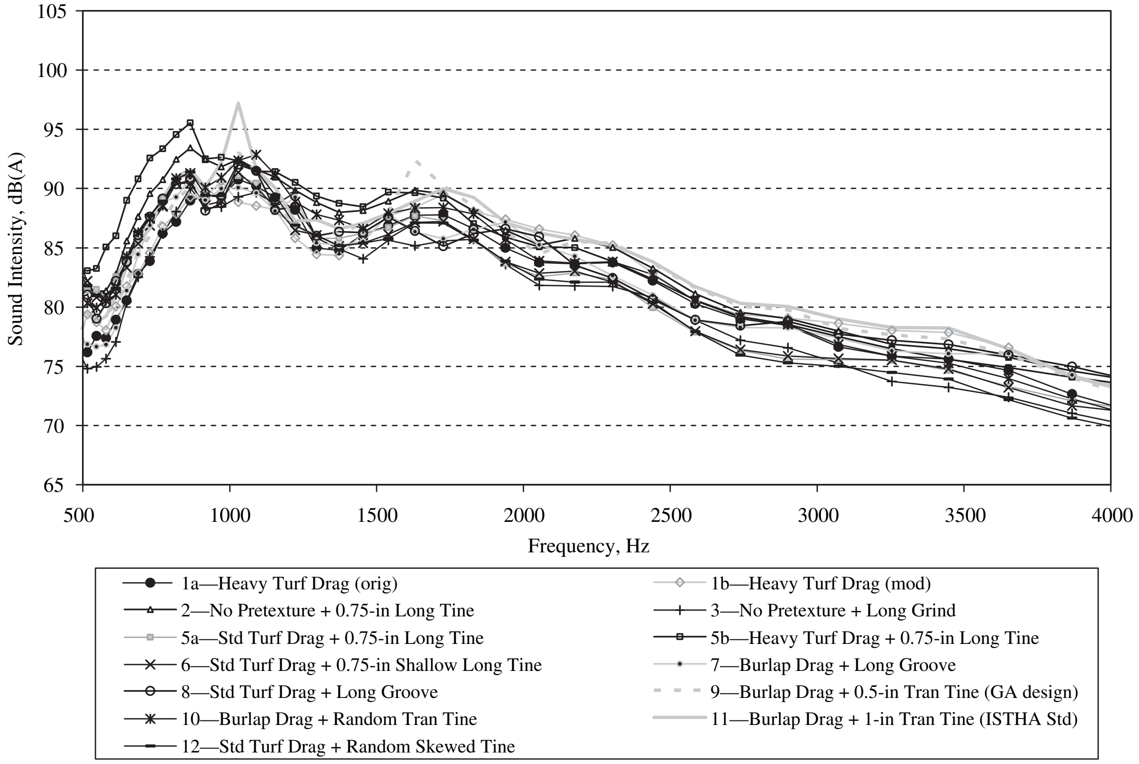


Figure 5-9. SI noise spectra for the newly constructed test sections.

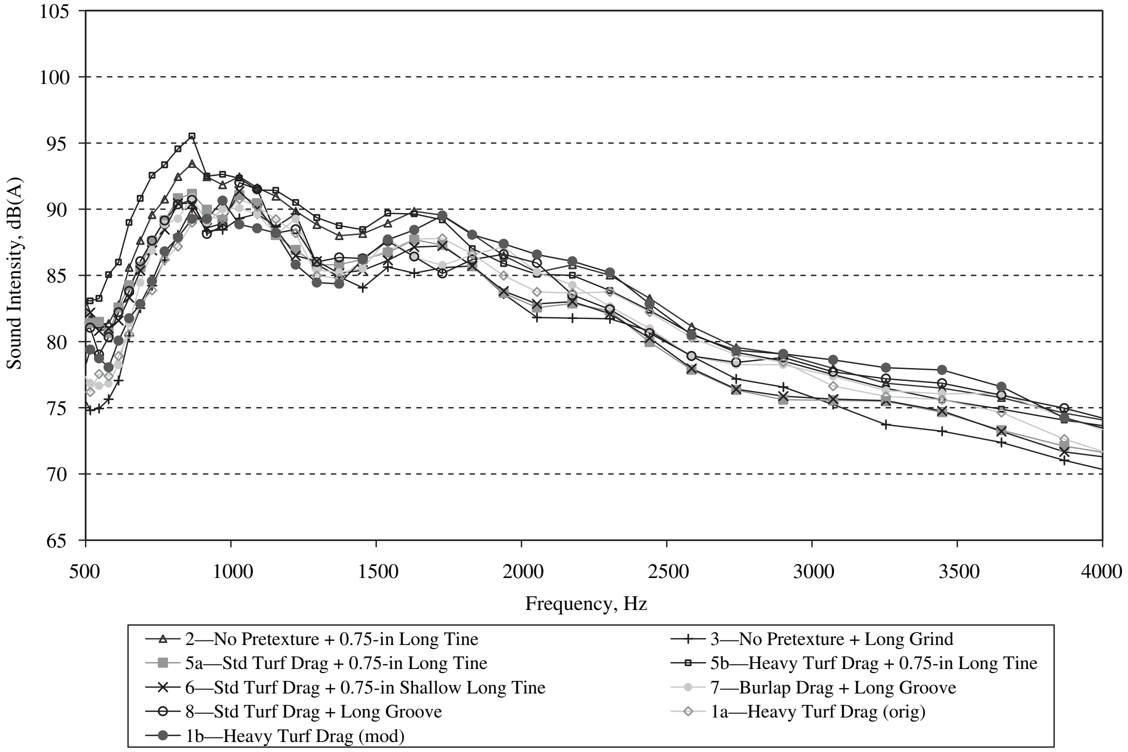


Figure 5-10. SI noise spectra for longitudinal textures test sections.

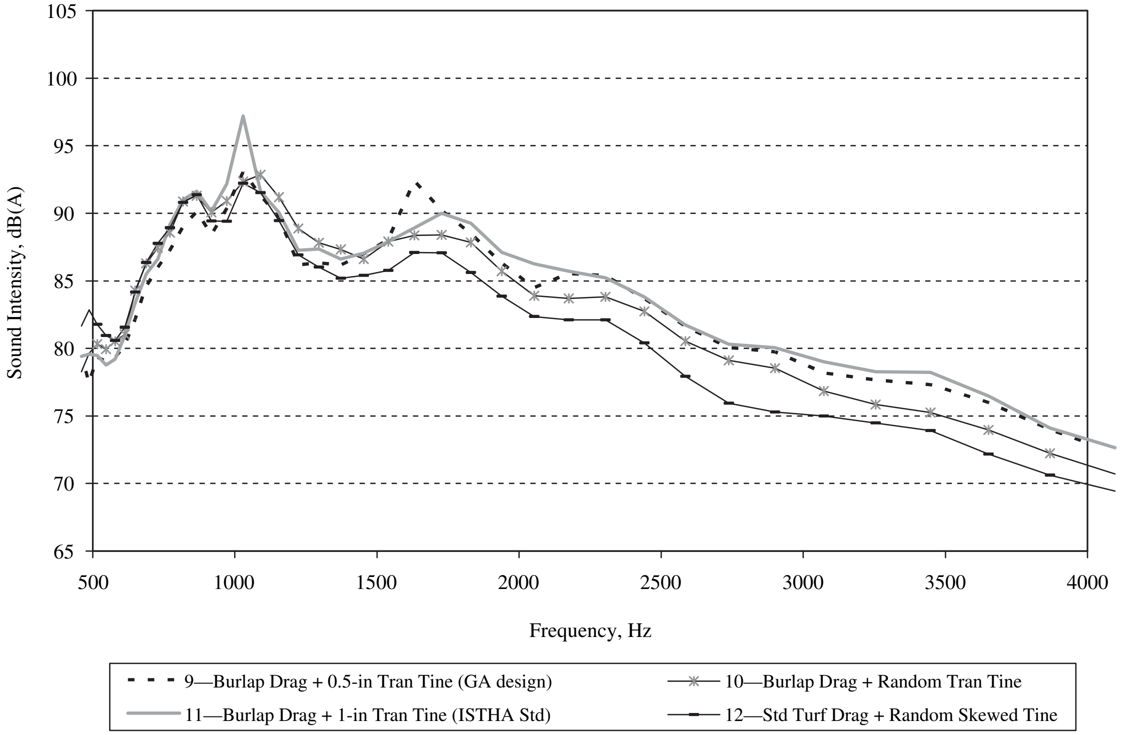


Figure 5-11. SI noise spectra for transverse textures test sections.

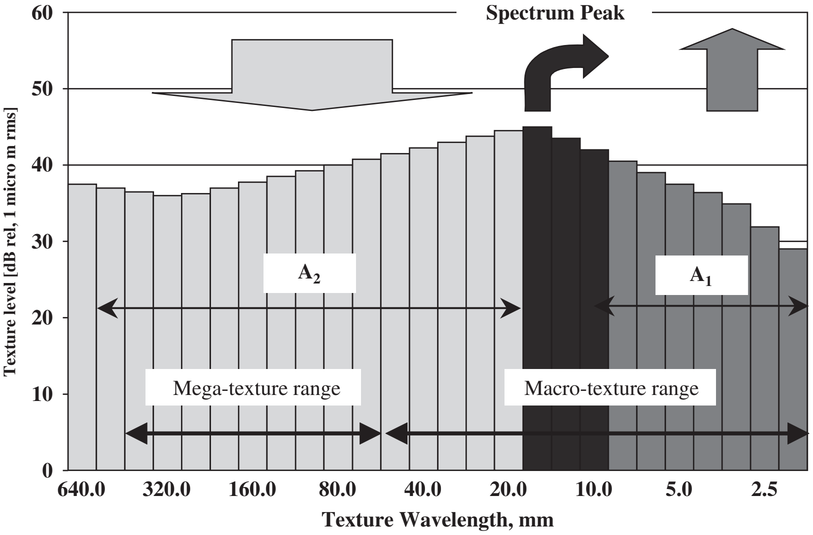


Figure 5-12. Texture spectrum characteristics for low noise.

610 mm) wavelength range should be reduced, texture in the 0.08 to 0.40 in. (2 to 10 mm) range should be increased, and the spectrum peak should occur at the lowest wavelengths possible, as illustrated in Figure 5-12. Also, two measures derived from the texture spectrum (L_4 and L_{63}) reportedly are good predictors of pavement–tire noise, as illustrated in Figure 5-13 (Sandberg and Ejsmont, 2002). L_4 and L_{63} are defined as follows:

- L_4—Profile level of the 0.16-in. (4-mm) octave band, represented by an energetic average of the third-octave bands 0.12, 0.16, and 0.20 in. (3.15, 4, and 5 mm); it is associated with high-frequency noise development.
- L_{63}—Profile level of the 2.48-in. (63-mm) octave band represented by an energetic average of the third-octave bands 2.0, 2.5, and 3.15 in. (50, 63, and 80 mm); it is associated with low-frequency noise development.

The texture profile level represented on the y-axis in Figures 5-12 and 5-13 is expressed in decibels relative to a reference RMS value of 1 µm (ISO, 2002).

To evaluate the significance of texture spectral parameters, the profile data collected on the newly constructed sections (right wheelpath for each 528-ft [161-m] test segment) were processed using the MatLab® PSD software program to obtain texture spectra for each section and compute the L_4 and L_{63} profile levels. Two other PSD parameters were also calculated.

- A_1—Texture content for the desirable wavelength range of 0.08 to 0.40 in. (2 to 10 mm).
- A_2—Texture content for the undesirable wavelength range of 0.80 to 24 in. (20 to 610 mm).

The corresponding ratios of L_4/L_{63} and A_1/A_2 were also computed and the locations of the spectrum peaks (in terms

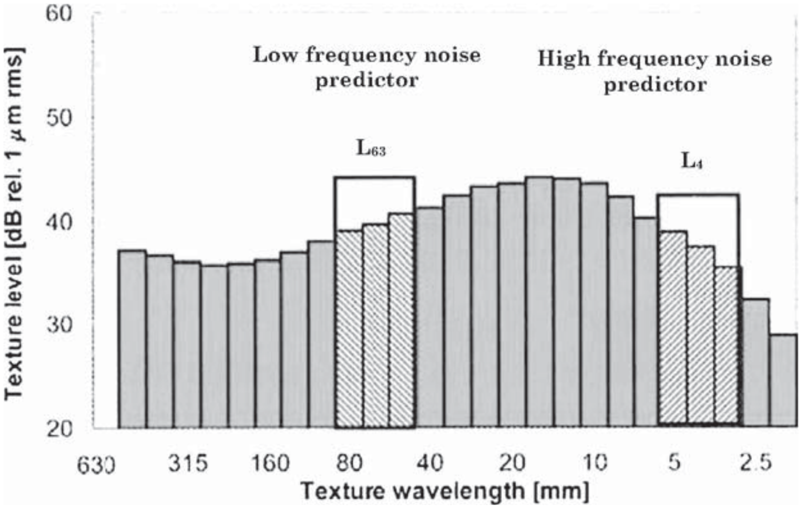


Figure 5-13. Texture spectrum profile levels.

Table 5-1. Summary of PSD texture parameters for new test sections.

Sect No.	Texture Description	L_4	L_{63}	L_4/L_{63}	A_1	A_2	A_1/A_2	Peak Spectrum Wavelength, mm
1a	Long Heavy Turf Drag	51	51	1	411	621	0.66	25
1b	Long Heavy Turf Drag (mod)	44	50	0.88	357	667	0.54	30
2	Long Tine (0.75-in. spacing, 0.125-in. depth), no pretexture	35	47	0.74	286	659	0.43	70
3	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers)	53	50	1.06	428	776	0.55	25
5a	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	32	44	0.73	258	608	0.43	50
5b	Long Tine (0.75-in. spacing, 0.125-in. depth), heavy turf drag	23	39	0.59	193	486	0.40	50
6	Long Tine (0.75-in. spacing, 0.075-in. depth), turf drag	34	47	0.72	277	640	0.43	65
7	Long Groove (0.75-in. spacing, 0.25-in. depth), burlap drag	28	21	1.33	225	322	0.70	15
8	Long Groove (0.75-in. spacing, 0.25-in. depth), turf drag	35	32	1.09	289	464	0.62	15
9	Tran Tine (0.5-in. spacing, 0.125-in. depth), burlap drag (GA design)	51	60	0.85	385	796	0.48	40
10	Tran Tine (variable spacing, 0.125-in. depth), burlap drag	40	52	0.77	308	699	0.44	45
11	Tran Tine (1.0-in. spacing, 0.125-in. depth), burlap drag (old ISTHA std)	39	52	0.75	305	682	0.45	40
12	Tran Skew Tine (variable spacing, 0.125-in. depth), turf drag (new ISTHA std)	38	47	0.81	310	636	0.49	40

of wavelength) were determined. Table 5-1 summarizes the PSD values obtained for the various textures. The resulting texture spectra showed peaks occurring at considerably lower wavelengths for the heavy turf drag textures and the diamond-ground and groove textures, which were among the quietest textures.

Figures 5-14 through 5-16 are plots of near-field SI as functions of L_4/L_{63}, A_1/A_2, and peak spectrum, respectively. These data show a somewhat linear relationship between SI and L_4/L_{63} and between SI and A_1/A_2. These relationships hold to the principles of reducing higher wavelength texture and increasing lower wavelength texture in order to reduce noise.

The three relationships were expected to be limited because noise depends on other factors (e.g., texture depth, direction, and orientation; and pavement porosity and stiffness) besides spectral characteristics. In addition to a relatively small data set, the two-dimensional profile used to represent a three-dimensional profile from which the actual noise was measured also limited the relationship.

Comparative/Qualitative Analyses

This analysis considers data obtained from the measurements on the existing and newly constructed test sections to develop a basic understanding of each texture's performance characteristics in terms of micro- and macro-texture, friction, and noise. The analysis included the following:

- Comparison of textures by site/location.
- Texture durability analysis.
- Comparison of textures by noise.

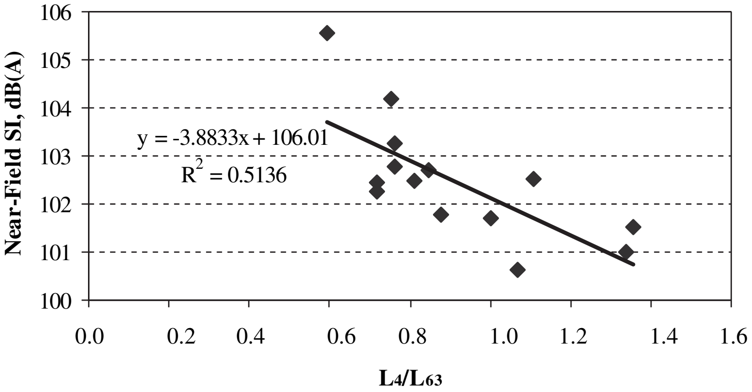


Figure 5-14. Near-field SI noise versus L_4/L_{63} profile level ratio.

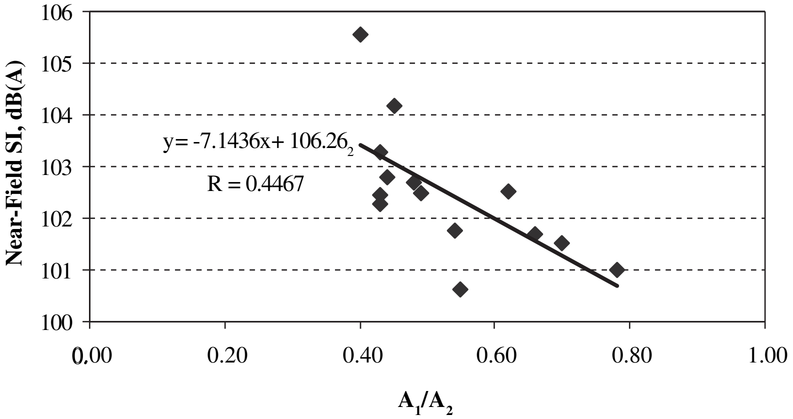


Figure 5-15. Near-field SI noise versus A_1/A_2 ratio.

- Relationship of near-field noise with interior and pass-by noise.
- Texture variability analysis.

Comparison of Textures by Site/Location

In this analysis, the textures at the different test sites/locations were compared and ranked in terms of their relative performance as defined by qualitative friction and noise levels. Summary tables were prepared that present the texture, friction, noise, and smoothness results (mean values) for each texture, and the corresponding rankings (1=best, 2=next best, etc.) for friction, noise, and smoothness. Key observations are then made concerning the rankings and overall qualitative performance.

The relative rankings of each set of test results are provided in parentheses in the summary tables. In some cases (e.g., Illinois Tollway, Colorado US 287), the test results were obtained before opening the road to traffic, thus reflecting an untrafficked pavement. In other cases (e.g., Arizona SR 202, California SR58), two sets of test results reflecting different levels of cumulative traffic were presented for tests in the wheelpath and at the lane center. In these cases, traffic data (yearly ADT values and truck percentages, estimated directional and lane distribution factors) provided by the respective state DOTs were used to estimate cumulative combined traffic (cars and trucks) and truck traffic applications at time of testing, using the following assumptions:

- The right wheelpath (defined by an 18-in. [460-mm] wide swath) experiences 90 to 95 percent of the combined lane traffic.
- The lane center (defined by an 18-in. [460-mm] wide swath), equally spaced between wheelpaths experiences 1 percent of the combined traffic and 0.5 percent of the truck traffic.

For evaluating the effect of traffic on the performance of textures, traffic levels were categorized as low traffic (less than 5,000,000 cumulative vehicles and/or less than 500,000 cumulative trucks) and high traffic (more than 5,000,000 cumulative vehicles and/or more than 500,000 cumulative trucks).

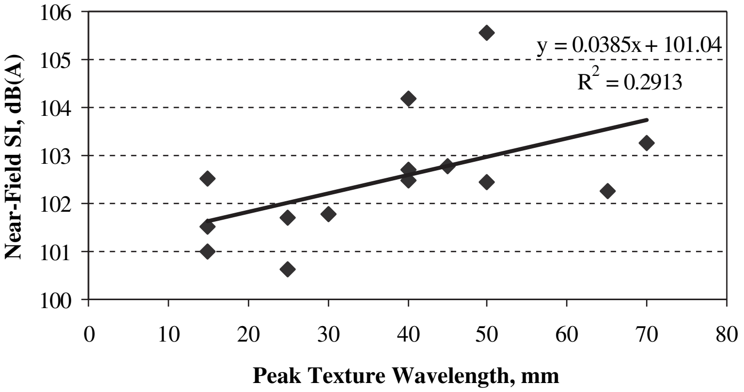


Figure 5-16. Near-field SI noise peak texture wavelength.

Because there are no established criteria for defining what is good, fair, and poor with respect to friction and noise, it was necessary to establish and apply some form of criteria to the test results to aid in the development of a texture selection process. Using information from the literature (e.g., Pottinger and Yager, 1986; Wambold, Henry, and Hegmon, 1986; Rasmussen et al., 2007b), the ranges of friction and noise shown in Table 5-2 were identified and used as qualitative indicators.

Arizona Sections

The four diamond-ground sections at this site, located on SR 202L in Phoenix, were constructed in summer 2003 and opened to traffic in fall 2003. Texture, friction, and noise testing was performed approximately 2 years later. The four textures are as follows:

- 1001—Long DG (no jacks), 0.235-in. (6.0-mm) spacing (i.e., 0.11-in. [2.8-mm] spacers).
- 1002—Long DG (jacks), 0.235-in. (6.0-mm) spacing (i.e., 0.11-in. [2.8-mm] spacers).
- 1003—Long DG (no jacks), 0.245-in. (6.2-mm) spacing (i.e., 0.12-in. [3.0-mm] spacers), fins scraped with motor grader at time of construction.
- 1004—Long DG (jacks), 0.245-in. (6.2-mm) spacing (i.e., 0.12-in. [3.0-mm] spacers).

Table 5-3 summarizes the texture, friction, and noise data collected on these sections, including test measurements made by the state DOT (Scofield, 2003) at the time of construction. The following are key observations concerning the performance of these sections (the noise comparisons discussed below are based only on relative rankings associated with each noise parameter [i.e., CPX during construction, SI for low traffic and high traffic]):

- In comparison to Section 1002, Section 1004 with wider groove spacing and lower texture depth and TR exhibited lower noise and lower friction.
- Section 1003 with the highest texture depth and TR has produced the highest near-field and interior noise and highest level of friction, and indicated that smoothness may have some direct effect on noise.
- Sections 1003 and 1004 that exhibited the greatest texture deterioration rates (MTD reduction of 0.02 to 0.03 mm per million vehicles [0.1 to 0.58 mm per million trucks]) showed mixed effects on friction and noise (Section 1003 showed no or only slight change in friction and noise, and Section 1004 showed large reduction in friction and only slight change in noise).
- Texture, friction, and noise were not noticeably affected by use of jacks.
- Noise spectra did not identify tonal issues for any of the textures.

California Sections

The surface textures on these sections were constructed between fall 2002 and summer 2003. The facility was opened to traffic in fall 2003, and texture, friction, and noise measurements were made about 2 years later. These sections are described as follows:

- 1002—Long DG (no jacks), 0.245-in. (6.2-mm) spacing (i.e., 0.12-in. [3.0-mm] spacers).
- 1003—Long groove, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, burlap drag.
- 1004—Long groove, 0.75-in. (19-mm) spacing, 0.25-in. (6.4-mm) depth, burlap drag.
- 1045—Long burlap drag
- 1005—Long DG (no jacks), 0.23-in. (5.8-mm) spacing (i.e., 0.105-in. [2.7-mm] spacers).
- 1007—Long groove, 0.375-in. (9.5-mm) spacing, 0.25-in. (6.4-mm) depth, broom drag.
- 1075—Long broom drag.

Table 5-4 summarizes the texture, friction, and noise information collected on the sections, including test measurements made at the time of construction by Caltrans (Donavan, 2003). Key observations concerning the performance of these sections are as follows:

- Drag-textured sections (1045 and 1075) had the lowest texture depths and generally showed lowest levels of friction. However, the effect of texture depth on noise was inconsistent. Section 1045 with burlap drag texture showed moderate near-field and interior noise, and the sections

Table 5-2. Qualitative designations for friction and noise parameters.

Qualitative Designation	Friction Parameters			Noise Parameters	
	FN40R	FN40S	IFI F(60)	Near-Field SI, dB(A)	Interior Noise L_{eq}, dB(A)
Low	<35	<28	<28	<102	<69
Moderate	35 to 45	28 to 40	28 to 40	102 to 106	69 to 72.5
High	>45	>40	>40	>106	>72.5

Table 5-3. Summary of test results for Arizona SR 202L texture sections.

Sect	Construction[1]					Low Traffic (LC)[2]							High Traffic (WP)[3]						
	Texture		Smooth	Friction	Noise	Texture			Smooth	Friction	Noise		Texture			Smooth	Friction	Noise	
	Design Groove Depth, mm	Actual Groove Depth, mm	IRI, in./mi	RFT	Near Field CPX, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)
1001	3.2-6.4	–	32.7 (2)	65 (4)	97.5 (3)	0.71	1.07	2.37 (2)	73.2 (2)	41.9 (2)	104.6 (1)	70.3 (1)	0.71	1.04	2.24 (2)	69.4 (1)	41.5 (2)	104.4 (1)	70.4 (2)
1002	3.2-6.4	–	34.2 (3)	66 (3)	98.0 (4)	0.72	1.12	2.41 (3)	80.7 (3)	40.8 (3)	105.6 (3)	71.4 (3)	0.70	1.07	2.27 (3)	80.9 (3)	39.2 (3)	105.8 (3)	72.2 (3)
1003	3.2-6.4	–	28.9 (1)	69 (1)	97.0 (2)	0.92	1.75	2.49 (4)	98.1 (4)	46.4 (1)	106.4 (4)	73.5 (4)	0.92	1.56	2.42 (4)	94.0 (4)	47.4 (1)	106.3 (4)	73.5 (4)
1004	3.2-6.4	–	38.5 (4)	67 (2)	95.5 (1)	0.73	0.87	1.89 (1)	70.8 (1)	36.5 (4)	104.7 (2)	70.3 (1)	0.64	0.70	1.58 (1)	74.2 (2)	32.2 (4)	104.9 (2)	69.9 (1)

1 in. = 25.4 mm   1 in./mi = 15.78 mm/km

[1] Measurements by Arizona DOT.

[2] Estimated 58,000 to 93,000 cumulative vehicles (1,600 to 11,000 cumulative trucks).

[3] Estimated 5,800,000 to 9,300,000 cumulative vehicles (319,000 to 2,100,000 cumulative trucks).

RFT=Runway Friction Tester

Note: Values in parentheses represent relative rankings for the respective test parameter.

Table 5-4. Summary of test results for California SR 58 texture sections.

	Construction[1]					Low Traffic (LC)[2]							High Traffic (WP)[3]						
	Texture		Smooth	Friction	Noise	Texture			Smooth	Friction	Noise		Texture			Smooth	Friction	Noise	
Sect	Design Groove Depth, mm	Actual Groove Depth, mm	IRI, in./mi	CFT	SI, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)
1002	1.6-3.2	–	–	46.5 (1)	102.3 (6)	0.71	0.96	1.97 (6)	60.5 (2)	40.1 (3)	105.1 (7)	68.8 (2)	0.67	0.67	1.77 (7)	55.1 (1)	33.7 (3)	106.2 (5)	68.9 (2)
1003	3.2	–	–	42.0 (4)	101.6 (3)	0.80	1.12	0.69 (2)	159.2 (6)	41.4 (2)	104.5 (4)	69.2 (4)	0.76	1.08	0.75 (2)	145.6 (5)	36.7 (2)	105.1 (3)	69.7 (3)
1004	6.4	–	–	41.0 (5)	102.0 (4)	1.00	1.31	0.57 (1)	156.7 (5)	44.7 (1)	104.9 (6)	69.5 (5)	0.89	1.29	0.52 (1)	172.7 (6)	38.3 (1)	105.6 (4)	70.3 (5)
1045	–	–	–	–	101.4 (2)	0.63	0.35	1.84 (4)	78.5 (4)	38.2 (5)	104.0 (1)	68.9 (3)	0.63	0.36	1.55 (4)	90.0 (4)	33.1 (4)	104.9 (2)	69.7 (3)
1005	1.6-3.2	–	–	45.5 (2)	100.9 (1)	0.67	0.90	2.00 (7)	58.4 (1)	37.7 (6)	104.4 (3)	67.8 (1)	0.64	0.73	1.65 (5)	56.6 (3)	31.9 (6)	104.5 (1)	67.9 (1)
1007	6.4	–	–	44.0 (3)	102.8 (7)	0.73	1.54	0.86 (3)	64.6 (3)	39.1 (4)	104.7 (5)	70.6 (7)	0.70	1.62	0.88 (3)	56.1 (2)	32.9 (5)	106.5 (7)	71.2 (6)
1075	–	–	–	–	102.2 (5)	–	0.33	1.89 (5)	–	26.0 (7)	104.3 (2)	70.5 (6)	–	0.35	1.65 (5)	–	22.4 (7)	106.2 (5)	71.5 (7)

1 in. = 25.4 mm 1 in./mi = 15.78 mm/km

[1] Measurements by Caltrans.

[2] Estimated 36,000 to 54,000 cumulative vehicles (7,000 to 11,000 cumulative trucks).

[3] Estimated 3,600,000 to 5,400,000 cumulative vehicles (1,400,000 to 2,100,000 cumulative trucks).

CFT=California Friction Tester

Note: Values in parentheses represent relative rankings for the respective test parameter.

with broom drag texture showed a high level of near-field noise.

- Diamond-ground sections (1002 and 1005) that had the second lowest texture depths showed differing friction and noise results. The narrower spacing of Section 1005 resulted in the lowest overall near-field and interior noise and one of the lowest levels of friction. The wider spacing of Section 1002 resulted in higher friction and relatively low interior noise, but the highest near-field noise of all sections.
- Longitudinal grooved sections (1003, 1004, and 1007) had the highest texture depths and lowest TR values. Friction was highest for the sections with wider spacing textures (1003 and 1004) and lower for the sections with narrower texture spacing (1007). Narrower texture spacing has shown the highest (or nearly highest) near-field and interior noise. Although differences were small, the shallower groove depth (0.125 in. [3.2 mm]) and correspondingly lower texture depth of Section 1003 resulted in slightly lower friction and slightly lower noise than that of Section 1004 with the deeper groove depth (0.25 in. [6.4 mm]).
- Effect of smoothness on noise was not consistent. The smoothest sections (1002, 1005, and 1007) exhibited the highest and lowest noise levels, and the roughest sections (1003 and 1004) exhibited moderate noise levels.
- Diamond-ground Sections 1002 and 1005 showed the greatest texture deterioration rates (MTD of 0.03 to 0.05 mm per million vehicles [0.08 to 0.14 mm per million trucks]); however, friction and noise deterioration rates were generally similar to those of other texture sections.
- Noise spectra did not identify tonal issues for any of the textures.

Colorado Sections

Sections on I-70. These test sections, located near Agate/Deer Trail, were constructed between July and September 1994, and opened to traffic in the October–November 1994 timeframe. Texture, friction, and noise measurements were made approximately 11 years later, in October 2005. These test sections are described as follows:

- 1007—Long groove, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, turf drag.
- 1008—Long turf drag.
- 1009—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, turf drag.

Table 5-5 summarizes the texture, friction, and noise information collected on these sections, including test measurements made by Colorado DOT at the time of construction (Ardani and Outcalt, 2005). Key observations concerning the performance of these sections are as follows:

- Longitudinal Drag Section 1008 with the lowest texture depth consistently showed the lowest levels of friction and noise with time/traffic. Although F(60) values derived from the DF Tester measurements showed moderate levels of friction in 2005, earlier locked-wheel friction tests by CDOT showed low friction FN40S values for this section.
- Longitudinal groove and longitudinal-tine sections (1007 and 1009) had similar texture depths initially, but the section with tine texture exhibited greater reduction in depth with time/traffic. Friction levels over time/traffic for these two textures have been similar. Near-field and interior noise has been consistently highest for the longitudinal-tine section.
- No effect of smoothness on noise was evident. The smoothest section (1008) exhibited the lowest noise, but the roughest section (1007) exhibited lower noise than the second smoothest section (1009).
- Texture deterioration has been highest for the longitudinal-tine section (1009) with MTD reduction of 0.005 mm per million vehicles (0.01 mm per million trucks) and lowest for the longitudinal groove section (1007). Effects of texture deterioration on friction and noise were not clear. All sections experienced similar friction deterioration rates, and the longitudinal-tine section (1009) experienced the lowest rate of increase in noise.
- Noise spectra identified no tonal issues for any of the textures.

Sections on US 287. These test sections, located on US 287 near Berthoud, were constructed between fall 2004 and summer 2005. Texture, friction, and noise measurements were made in fall 2005 (long before opening to traffic in June 2006). Descriptions of these test sections are as follows:

- 3001—Long heavy turf drag.
- 3002—Long tine, 0.75-in. (19-mm) spacing, 0.1875-in. (4.9-mm) depth, no pretexture.
- 3003—Long meander tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, no pretexture.
- 3004—Long groove, 0.75-in. spacing (19-mm), 0.125-in. (3.2-mm) depth, turf drag.
- 3005—Long DG (no jacks), 0.22-in. (5.6-mm) spacing (i.e., 0.095-in. [2.4-mm] spacers).
- 3006—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, turf drag.

Table 5-6 summarizes the texture, friction, and noise information collected on the test sections. Because measurements were made prior to opening of the facility to traffic, an assessment of the effects of traffic could not be made. The following

Table 5-5. Summary of test results for Colorado I-70 sections.

Sect No.	Construction[1]								Low Traffic (LC)[2]			High Traffic (WP)[3]						
	Texture			Smooth	Friction		Noise		Texture		Friction	Texture			Smooth	Friction	Noise	
	Design Groove Depth, mm	Actual Groove Depth, mm	Sand Patch MTD, mm	$PI_{0.2}$, in./mi	FN40R	FN40S	Near Field SPL, dB(A)	Int SPL, dB(A)	CTM MTD, mm	CTM TR	DFT F(60)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)
1007	3.2	5.81	1.24	1.7 (1)	53.1 (2)	55.2 (2)	99 (1)	66 (1)	1.30	0.92 (2)	48.4 (1)	1.08	1.41	0.97 (1)	199 (3)	42.8 (2)	105.9 (2)	69.4 (2)
1008	–	0.79	0.51	1.7 (1)	52.0 (3)	30.4 (3)	99 (1)	66 (1)	0.37	1.78 (3)	39.8 (3)	0.67	0.34	1.62 (3)	107 (1)	36.6 (3)	104.4 (1)	68.6 (1)
1009	3.2	3.96	1.19	1.8 (3)	64.4 (1)	56.4 (1)	101 (3)	68 (3)	0.93	1.08 (1)	47.5 (2)	0.98	0.86	1.05 (2)	131 (2)	44.1 (1)	106.1 (3)	69.8 (3)

1 in. = 25.4 mm 1 in./mi = 15.78 mm/km

[1] Measurements by Colorado DOT.

[2] Estimated 145,000 cumulative vehicles (30,000 cumulative trucks).

[3] Estimated 14,500,000 cumulative vehicles (5,900,000 cumulative trucks).

SPL = Sound Pressure Level

Note: Values in parentheses represent relative rankings for the respective test parameter.

Table 5-6. Summary of test results for Colorado US 287 sections.

Sect No.	Construction—No Traffic (all measurements based on testing in right wheelpath)								
	Texture				Smooth	Friction	Noise		
	Design Groove Depth, mm	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	Far Field CPB, dB(A)
3001	–	0.93	0.88	1.87 (5)	73.5 (2)	52.4 (3)	103.1 (2)	69.7 (3)	77.8
3002	4.8	0.96	1.03	1.26 (1)	92.6 (4)	54.6 (2)	104.3 (4)	70.4 (5)	–
3003	3.2	1.12	1.08	1.36 (2)	84.9 (3)	56.0 (1)	104.4 (6)	71.4 (6)	–
3004	3.2	0.80	1.03	1.47 (3)	123.2 (6)	44.4 (5)	104.3 (4)	69.2 (2)	78.6
3005	1.6	0.67	0.91	2.44 (6)	59.7 (1)	43.8 (6)	102.7 (1)	68.1 (1)	–
3006	3.2	0.92	0.81	1.51 (4)	98.3 (5)	50.7 (4)	103.8 (3)	69.9 (4)	–

1 in. = 25.4 mm   1 in./mi = 15.78 mm/km

Note: Values in parentheses represent relative rankings for the respective test parameter.

are key observations concerning the performance of these sections:

- Sections with the lowest texture depths (3006 [longitudinal-tine-standard groove depth], 3001 [heavy turf drag], and 3005 [longitudinal DG]) exhibited the lowest near-field noise levels and friction values in the mid to low range.
- Sections with the highest texture depths (3002 [longitudinal-tine-deeper groove), 3003 [longitudinal meander tine], and 3004 [longitudinal groove]) generally yielded the highest near-field and interior noise and the highest friction; the exception being the longitudinal groove texture that exhibited the second lowest friction and the second lowest interior noise.
- Comparison of Sections 3006 and 3002 (longitudinal-tine with standard and deeper grooves, respectively) indicated the opposite effects of texture depth on friction and noise. Also, Section 3003 (longitudinal meander tine with standard grooves) resulted in higher texture depth than Section 3006.
- Higher texture ratios corresponded to lower noise levels. Smoothness may have contributed to this trend, as exhibited by Sections 3004 (roughest) and 3005 (smoothest).
- Noise spectra identified no tonal issues for any of the textures.

Iowa Sections

Sections on US 163. The test sections on US 163 near Des Moines were constructed in fall 1993 and opened to traffic in 1994. Texture, friction, and noise measurements were made in August 2005. Descriptions of the test sections are as follows:

- 1002—Tran tine, 0.5-in. (12.7-mm) spacing, 0.075-in. (1.9-mm) depth, turf drag.
- 1003—Long tine, 0.5-in. (12.7-mm) spacing, 0.075-in. (1.9-mm) depth, turf drag.
- 1004—Long tine, 0.75-in. (19-mm) spacing, 0.15-in. (3.8-mm) depth, turf drag.
- 1061—Tran groove, 1-in. (25.4-mm) spacing, 0.1875- to 0.25-in. (4.8- to 6.4-mm) depth, turf drag.
- 1007—Long turf drag.

Table 5-7 summarizes the texture, friction, and noise information collected on the sections, including test measurements made by Iowa DOT at the time of construction (Marks, 1996). Key observations concerning the performance of these textures are as follows:

- Comparable texture depths were obtained from the high-speed profiler for the five textures. Friction levels on these sections were considerably higher than those for other sections, as indicated by the IFI F(60) values derived from FN40S measurements.
- The narrower spacing and shallower depth of the tine profile in Section 1003 yielded slightly lower near-field and interior noise levels than that for Section 1004.
- The longitudinal turf drag (Section 1007) exhibited low friction values.
- The longitudinal turf drag section appeared to be the quietest surface initially (for internal noise), but was surpassed by the two longitudinal-tine textures and was assigned a qualitatively "high" noise level.
- Transverse-tine and groove textures (Sections 1002 and 1061) were assigned qualitatively "high" near-field noise levels with the latter assigned a qualitatively "high" level for interior noise. However, friction levels on both sections were considerably lower than those for the longitudinal-tine sections (1003 and 1004).
- All sections exhibited comparable texture depth deterioration rates, ranging from 0.006 to 0.009 mm per million vehicles [0.04 to 0.05 mm per million trucks]. Considering the snowfall experienced at this location, a portion of

Table 5-7. Summary of test results for Iowa US 163 sections.

Sect No.	Construction[1]				Low Traffic (LC)[2]				High Traffic (WP)[3]				
	Texture		Friction	Noise	Texture	Smooth	Noise		Texture	Smooth	Friction	Noise	
	Design Groove Depth, mm	Actual Groove Depth, mm	FN40R	Int Noise Panel Rating	HS EMTD, mm	IRI, in./mi	Near Field SI, dB(A)	Int L_{eq}, dB(A)	HS EMTD, mm	IRI, in./mi	FN40S F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)
1002	1.9	2.25	52	5.7 (4)	1.12	103.4	105.2 (2)	70.7 (1)	0.98	107.3	36.6 (3)	107.6 (4)	71.7 (2)
1003	1.9	2.50	48	2.4 (2)	1.09	118.9	105.3 (3)	71.1 (2)	0.96	113.8	41.4 (2)	105.6 (1)	71.3 (1)
1004	3.8	4.00	49	3.0 (3)	1.09	125.1	105.9 (4)	72.1 (3)	0.96	134.5	43.3 (1)	106.5 (2)	72.3 (3)
1061	4.8-6.4	–	–	–	1.09	106.8	108.6 (5)	74.1 (4)	1.00	103.9	36.3 (4)	109.4 (5)	74.3 (5)
1007	–	–	41	1.6 (1)	1.12	129.0	105.0 (1)	71.1 (2)	1.01	126.6	17.8 (5)	106.6 (3)	73.1 (4)

1 in. = 25.4 mm 1 in./mi = 15.78 mm/km

[1] Measurements by Iowa DOT.

[2] Estimated 158,000 cumulative vehicles (12,600 cumulative trucks).

[3] Estimated 15,800,000 cumulative vehicles (2,500,000 cumulative trucks).

Note 1: Values in parentheses represent relative rankings for the respective test parameter.

Note 2: Panel rating for interior noise based on 1-to-10 scale (1=unobjectionable, 10=very objectionable)

these texture deterioration rates could be the result of frequent snowplow use.
- Sections 1002 and 1003 exhibited definite tonal spikes around 1,500 Hz, indicative of high-frequency whine.

Sections on US 34. The test sections on US 34 Bypass north of Mt. Pleasant were constructed in fall 2004. Texture, friction, and noise measurements were made just prior to opening to traffic in fall 2005 (DF Tester and CT Meter testing was performed about 6 months later in 2006). The two test sections are described as follows:

- 2001—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth), turf drag.
- 2002—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, burlap drag.

Table 5-8 summarizes the texture, friction, and noise data collected on the two sections. Some key observations concerning the performance of these sections are as follows:

- The slightly lower texture depth in Section 2001 appears to have contributed to lower near-field and interior noise on this section than on Section 2002.
- The more aggressive pre-texturing associated with turf drag on Section 2001 has likely resulted in higher friction levels on this section than on the other.
- Smoothness levels of the two sections are very similar, and thus smoothness was not a contributing factor to the different levels in noise.
- Noise spectra identified no tonal issues for any of the textures.

Kansas Sections

The test sections on US 69 near Louisburg were constructed in 2004 and opened to traffic in late 2004. Texture, friction, and noise measurements were made in September, 2005. Descriptions of the seven test sections are as follows:

- 1002—Long DG (no jacks), 0.235-in. (6-mm) spacing (i.e., 0.11-in. [2.8-mm] spacers), standard-sawed joints.
- 1004—Long DG (no jacks), 0.245-in. (6.2-mm) spacing (i.e., 0.12-in. [3.0-mm] spacers), single-sawed joints.
- 1005—Long DG (jacks), 0.255-in. (6.5-mm) spacing (i.e., 0.13-in. [3.3-mm] spacers), standard-sawed joints.
- 1006—Long DG (jacks), 0.255-in. (6.5-mm) spacing (i.e., 0.13-in. [3.3-mm] spacers), single-sawed joints.
- 1007—Long DG (no jacks), 0.255-in. (6.5-mm) spacing (i.e., 0.13-in. [3.3-mm] spacers), standard-sawed joints.
- 1008—Long DG (no jacks), 0.255-in. (6.5-mm) spacing (i.e., 0.13-in. [3.3-mm] spacers), single-sawed joints.
- 1010—Long tine, 0.75-in. (19-mm) spacing, 0.15-in. (3.8-mm) depth, turf drag.

Table 5-9 summarizes the texture, friction, and noise information collected on the test sections, including measurements made by others (Brennan and Schieber, 2006) at the time of construction. Key observations concerning the performance of these sections are as follows:

- The consistently higher texture depths for the four diamond-ground surfaces with 0.13-in. [3.3-mm] spacers resulted in moderately high rankings for friction and moderately low rankings for noise. Despite the low cumulative traffic, nearly all sections reached qualitatively "high" levels of interior noise. Specific comparisons of spacer widths (Section 1002 versus 1007 and Section 1004 versus 1008) show that wider blade spacing contributes to higher texture depth, higher friction, slightly to moderately higher near-field noise, higher interior noise, and greater roughness.
- The effect of using jacks in the diamond grinding process was not particularly noticeable. Comparisons of Sections 1005 and 1007 and Sections 1006 and 1008 revealed slight

Table 5-8. Summary of test results for Iowa US 34 sections.

	Construction (measurements based on testing in right wheelpath, unless indicated differently)									
	Texture				Smooth	Friction		Noise		
Sect No.	Design Groove Depth, mm	HS EMTD, mm	CTM MTD, mm[1]	CTM TR[1]	IRI, in./mi	DFT F(60)[1]	FN40S F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	Far Field CPB, dB(A)
2001	3.2	0.80	LC=0.73 WP=0.66	LC=1.27 WP=1.34	88.5 (2)	LC=27.8 WP=26.9	52.9 (1)	103.8 (1)	71.5 (1)	78.5
2002	3.2	0.89	LC=0.80 WP=0.71	LC=1.14 WP=1.13	88.0 (1)	LC=26.5 WP=26.1	51.1 (2)	105.3 (2)	72.8 (2)	80.5

1 in. = 25.4 mm   1 in./mi = 15.78 mm/km

[1] Testing with CT Meter and DF Tester performed approximately 6 months after facility opened to traffic. Estimated 750,000 cumulative vehicles applied to wheelpath and 7,500 cumulative vehicles applied to lane center (67,000 and 350 cumulative trucks).

Note: Values in parentheses represent relative rankings for the respective test parameter.

Table 5-9. Summary of test results for Kansas US 69 sections.

	Construction[1]					Low Traffic (LC)[2]							High Traffic (WP)[3]						
	Texture		Smooth	Friction	Noise	Texture			Smooth	Friction	Noise		Texture			Smooth	Friction	Noise	
Sect No.	Design Groove Depth, mm	Sand Patch MTD, mm	Ames LP IRI, in./mi	FN40R	Near Field SI, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)
1002	1.6	1.04	46.0 (6)	49.7 (7)	103.3 (1)	0.62	0.86	2.16 (6)	50.5 (1)	32.9 (7)	104.3 (1)	71.9 (1)	0.64	0.85	2.14 (2)	46.6 (1)	30.2 (7)	105.0 (1)	72.5 (1)
1004	1.6	1.14	37.2 (1)	51.5 (5)	103.5 (2)	0.68	0.85	2.22 (7)	60.5 (3)	34.4 (5)	105.0 (3)	72.6 (3)	0.71	0.88	2.37 (7)	63.5 (5)	32.3 (6)	106.0 (6)	72.5 (1)
1005	1.6	1.32	43.9 (4)	60.7 (1)	105.1 (5)	0.71	1.03	2.11 (3)	63.6 (5)	35.6 (3)	105.0 (3)	72.8 (5)	0.71	1.00	2.14 (2)	60.7 (2)	33.9 (4)	105.6 (4)	72.7 (3)
1006	1.6	1.45	40.1 (3)	57.1 (2)	105.2 (6)	0.69	1.04	2.10 (2)	63.5 (4)	35.3 (4)	105.0 (3)	72.5 (2)	0.72	1.01	2.16 (4)	62.5 (4)	33.2 (5)	105.8 (5)	72.8 (4)
1007	1.6	1.45	37.4 (2)	56.4 (3)	105.0 (4)	0.68	0.99	2.15 (5)	60.0 (2)	33.9 (6)	104.9 (2)	72.6 (3)	0.71	1.10	2.28 (6)	61.6 (3)	34.3 (3)	105.3 (2)	73.3 (5)
1008	1.6	1.30	44.2 (5)	55.1 (4)	104.2 (3)	0.87	0.95	2.12 (4)	96.7 (6)	39.2 (1)	105.9 (7)	73.7 (7)	0.92	1.00	2.23 (5)	99.6 (7)	38.7 (1)	106.9 (7)	74.5 (7)
1010	4.8	0.56	102.6 (7)	50.8 (6)	108.2 (7)	0.64	0.74	1.26 (1)	105.7 (7)	36.3 (2)	105.3 (6)	73.0 (6)	0.66	0.71	1.19 (1)	94.8 (6)	35.6 (2)	105.4 (3)	73.8 (6)

1 in. = 25.4 mm   1 in./mi = 15.78 mm/km

CPB Noise Measurements: Sect 1004 (77.8 dB(A))

[1] Measurements by Kansas DOT.

[2] Estimated 15,000 cumulative vehicles (1,500 cumulative trucks).

[3] Estimated 1,500,000 cumulative vehicles (300,000 cumulative trucks).

Three different testing devices—CA Profilograph, SD Profilometer, and Ames Lightweight Profiler (LP)—were used to measure smoothness, each giving different results.

For consistency purposes, Ames LP IRI measurements are listed.

Note: Values in parentheses represent relative rankings for the respective test parameter.

differences in texture depth, small differences in roughness, and small differences in friction that changed over time. The near-field and interior noise differences were negligible but the sections on which jacks were used were somewhat quieter than the others.

- The effect of joint width (standard 0.375-in. [9.5-mm] wide joint and single-cut 0.125-in. [3.2-mm] wide joint) on noise was also not particularly noticeable. Sections 1005 and 1006 showed similar texture depths and roughness and no apparent differences in near-field and interior noise. Sections 1007 and 1008 with 0.125-in. (3.2-mm) wide joints showed somewhat greater noise, but roughness could have been a contributing factor.
- The longitudinal-tine Section 1010, which had consistently the lowest texture depth, showed the highest level of near-field noise initially, but ranked more favorably with time/traffic. Interior noise levels for this texture ranked among the lowest and was qualitatively ranked "high."
- TR was not a consistent indicator of noise performance. The longitudinal-tine Section 1010 had the lowest TR, but was among the noisiest sections. The six diamond-ground test sections had very high TR values and moderately high noise levels.
- Texture deterioration rates varied from slightly negative deterioration (possibly as a result of pronounced wear by snowplows on the lane center) for three of the diamond-ground sections (1004, 1007, and 1008) to 0.01 to 0.02 mm per million vehicles [0.04 to 0.05 mm per million trucks] for the other three diamond-ground sections and the longitudinal-tine section (Sections 1002, 1005, 1006, and 1010). Although the lack of deterioration for the former three sections contributed to little or no change in friction, noise on these sections increased at similar rates to the other diamond-ground textures.
- Noise spectra identified no tonal issues for any of the textures.

Minnesota Sections

These sections on US 169 near Brooklyn Park were constructed in 1995 and opened to traffic in late 1995/early 1996. Texture, friction, and noise measurements were made about 10 years later in September 2005. Descriptions of the two test sections are as follows:

- 7001—Long turf drag.
- 8001—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, turf drag.

Table 5-10 summarizes the texture, friction, and noise information collected on the sections. No measurements were made at the time of construction; however, the sections were included in an earlier study (Kuemmel et al., 2000) and texture, friction, and interior noise data obtained in 1997 have been listed. Key observations concerning the performance of these sections are as follows:

- Turf drag Section 7001 exhibited lower texture depth and lower levels of friction and noise with time/traffic than that for the longitudinal-tine Section 8001. Both textures, however, were qualitatively ranked "high" for near-field noise, and the latter was ranked "high" for interior noise.
- Friction levels for both surfaces have remained adequate over the 10 years of service.
- Although Section 8001 was substantially rougher than Section 7001, both sections showed similar differences in near-field and interior noise levels obtained across test sections (i.e., wheelpath versus lane center).
- Texture deterioration rates (as determined by difference in wheelpath and lane center texture depths) were slightly negative for both sections, possibly as a result of wear caused by snowplows.
- Noise spectra identified no tonal issues for any of the textures.

North Dakota Sections

These sections on I-94 Glen Ullin were constructed in September 1999 and opened to traffic in late 1999/early 2000. Texture, friction, and noise measurements were made in September 2005. Descriptions of the two test sections are as follows:

- 2001—Long heavy turf drag.
- 2002—Tran tine, variable spacing, 0.1-in. [2.5-mm] depth, turf drag.

Table 5-11 summarizes the texture, friction, and noise information collected on these sections, including test measurements made by others (Marquart, 2003) at the time of construction. Key observations concerning the performance of these sections are as follows:

- The heavy turf drag section (2001) has shown greater texture depth and higher levels of friction and noise with time/traffic than the variably spaced transverse tine (2002). Both surfaces, however, were qualitatively ranked "high" for near-field noise, and the turf drag surface was ranked "high" for interior noise.
- Friction levels for both surfaces have remained adequate, likely due to the high-quality aggregate (granite) used.
- No effect of smoothness on noise was apparent.
- Texture deterioration (as determined by difference between wheelpath and lane center texture depth) has ranged from negligible for the variably spaced transverse tine (Section 2002) to 0.007 mm per million vehicles (0.023 mm per

Table 5-10. Summary of test results for Minnesota US 169 sections.

	Construction[1]	Low Traffic (LC)[2]							High Traffic (WP)[3]						
	Texture	Texture			Smooth	Friction	Noise		Texture			Smooth	Friction	Noise	
Sect No.	Design Groove Depth, mm	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)
7001	–	0.69	0.46	1.52 (2)	79.1 (1)	39.9 (2)	106.3 (1)	71.2 (1)	0.70	0.50	1.42 (2)	78.2 (1)	35.4 (2)	107.3 (1)	71.7 (1)
8001	3.2	0.93	0.95	1.16 (1)	168.2 (2)	46.0 (1)	107.7 (2)	72.5 (2)	0.89	1.00	1.08 (1)	184.9 (2)	41.3 (1)	108.6 (2)	73.1 (2)

1 in. = 25.4 mm   1 in./mi = 15.78 mm/km

[1] Measurements by Minnesota DOT.

[2] Estimated 650,000 cumulative vehicles (14,000 cumulative trucks).

[3] Estimated 6,500,000 cumulative vehicles (2,700,000 cumulative trucks).

Note 1: Values in parentheses represent relative rankings for the respective test parameter.

Note 2: 1997 test results from Marquette Noise and Texture study include the following:

Sect 7001: FN40S=48.8 IRI=64 in./mi ROSAN$_V$ EMTD = 0.28 mm Int Noise L_{eq} = 68.3

Sect 8001: FN40S=76.6 IRI=67.2 in./mi ROSANv EMTD = 0.77 mm Int Noise L_{eq} = 69.4

Table 5-11. Summary of test results for North Dakota I-94 test sections.

Sect No.	Construction[1]				Low Traffic (LC)[2]							High Traffic (WP)[3]						
	Texture		Friction	Noise	Texture			Smooth	Friction	Noise		Texture			Smooth	Friction	Noise	
	Design Groove Depth, mm	Sand Patch MTD, mm	FN40R	Int Noise, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	HS EMTD, mm	CTM MTD, mm	CTM TR	IRI, in./mi	DFT F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)
2001	–	0.90	43.0 (1)	68.1 (1)	0.91	0.67	1.23 (1)	80.5 (1)	47.9 (1)	109.8 (2)	72.4 (2)	0.88	0.64	1.21 (1)	93.0 (1)	39.6 (1)	110.8 (2)	73.8 (2)
2002	2.5	1.00	40.2 (2)	69.5 (2)	0.69	0.47	1.78 (2)	81.0 (2)	40.8 (2)	104.8 (1)	68.7 (1)	0.69	0.47	1.76 (2)	98.9 (2)	36.6 (2)	106.2 (1)	69.0 (1)

1 in. = 25.4 mm 1 in./mi = 15.78 mm/km

[1] Measurements by North Dakota DOT.

[2] Estimated 45,000 cumulative vehicles (6,500 cumulative trucks).

[3] Estimated 4,500,000 cumulative vehicles (1,300,000 cumulative trucks).

Note: Values in parentheses represent relative rankings for the respective test parameter.

million trucks) for the heavy turf drag (Section 2001). Despite no change in texture depth on Section 2002, friction has decreased and noise has increased somewhat.
- Noise spectra identified no tonal issues for any of the textures.

Illinois Tollway I-355 South Extension Newly Constructed Sections

The test sections at the Illinois Tollway were constructed in April/May and September/October 2007 and opened to traffic in November 2007. Texture, friction, and noise measurements were made 1 to 3 months prior to opening. Texture measurements included tine depth readings taken with a depth gauge (1) during construction, immediately behind the tining machine, (2) after a few weeks of construction traffic, and (3) several weeks after construction and before opening to traffic. Descriptions of the textures are again as follows:

- 1a—Long heavy turf drag.
- 1b—Long heavy turf drag (modified).
- 2—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, no pretexture.
- 3—Long DG (no jacks), 0.235-in. (6-mm) spacing (i.e., 0.11-in. [2.8-mm] spacers), no pretexture.
- 5a—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, turf drag.
- 5b—Long tine, 0.75-in. (19-mm) spacing, 0.125-in. (3.2-mm) depth, heavy turf drag.
- 6—Long tine, 0.75-in. (19-mm) spacing, 0.075-in. (2-mm) depth, turf drag.
- 7—Long groove, 0.75-in. (19-mm) spacing, 0.25-in. (6.4-mm) depth, burlap drag.
- 8—Long groove, 0.75-in. (19-mm) spacing, 0.25-in. (6.4-mm) depth, turf drag.
- 9—Tran tine, 0.5-in. (12.7-mm) spacing, 0.125-in. (3.2-mm) depth, burlap drag (GA design).
- 10—Tran tine, variable spacing, 0.125-in. (3.2-mm) depth, burlap drag.
- 11—Tran tine, 1.0-in. (25.4-mm) spacing, 0.125-in. (3.2-mm) depth, burlap drag (old ISTHA design).
- 12—Tran skewed tine, variable spacing, 0.125-in. (3.2-mm) depth, turf drag (new ISTHA design).

Table 5-12 summarizes the texture, friction, and noise information collected on these sections. Key observations concerning the performance of these textures are as follows:

- Turf drag sections (1a and 1b) exhibited the lowest texture depths and lowest levels of friction. Near-field noise was relatively low compared with most other surfaces, but interior noise was ranked high.
- Longitudinal grooved sections (7 and 8) were among the quietest textures, despite the relatively high texture depths. Negative texture orientation (TR<0.9) may have contributed to this phenomenon. The higher texture depth of Section 8 resulted in significantly greater friction than for Section 7.
- Performance of longitudinal-tine sections (2, 5a, 5b, and 6) varied. The section with the highest macro-texture (Section 5b), due in part to the heavy turf drag pretexture, had the greatest levels of friction and roughness. Section 5a, which used normal turf drag pretexture, had much lower friction and near-field noise, but similar interior noise. Section 2, which included no pretexture, also showed significantly less friction and noise. Standard- and shallow-depth longitudinal tining Sections 5a and 6 indicated similar levels of friction and near-field noise, but considerably lower interior noise for the latter.
- The diamond-ground Section 3 exhibited the lowest near-field and interior noise levels and its texture depth was fourth highest among all sections.
- Friction performance of the transverse tine sections was about the same as that for the longitudinal-tine section. The near-field noise levels for these textures were somewhat higher than those for the longitudinal, but the interior noise levels were slightly lower.
- Two transverse tine sections were found to have significant tonal spikes in the noise spectra. Section 9 (Georgia design with 0.5-in. [12.7-mm] spacing) showed a spike around 1,600 Hz, and Section 11 (old ISTHA design with 1.0-in. [25.4-mm] spacing) showed a spike around 1,000 Hz.
- Roughness may have contributed to the noise generated by longitudinal-tine on Sections 2 and 5b and by transverse tine on Section 11.

General Observations

- Diamond Grinding
  - Jacks versus no jacks—No notable differences observed at the sites in Arizona and Kansas.
  - TR—Typical values for diamond-ground sections ranged from 1.5 to 2.5, which exceeded the desirable range (<0.9 to 0.95) for "negative" texture orientation. In general, a lower TR of the diamond grind texture results in a lower noise level.
- Grinding versus Grooving—Although texture depths of ground sections in California and Colorado (US 287 [untrafficked]) were consistently lower than grooved sections, noise results varied (higher noise on California sites and slightly lower noise on Colorado sites). Friction levels for the ground sections at both locations were slightly lower than that for the grooved sections.

Table 5-12. Summary of test results for Illinois Tollway newly constructed test sections.

Sect No.	Construction—No Traffic (all measurements based on testing in right wheelpath)														
	Texture							Smooth		Friction			Noise		
	Design Groove Depth, mm	Groove Depth Behind Tiner, mm	Groove Depth After Const Traffic, mm	CTM Groove Depth, mm	HS EMTD, mm	CTM MTD, mm	CTM TR	$PI_{0.0}$, in./mi	IRI, in./mi	DFT F(60)	FNS F(60)	FNR F(60)	Near Field SI, dB(A)	Int L_{eq}, dB(A)	Far Field CPB, dB(A)
1a	–	–	–	–	0.51	–	–	21.2 (6)	76 (8)	23.5 (7)	–	30.6 (8)	101.7 (3)	69.5 (10)	–
1b	–	–	–	–	0.59	0.54	1.88	16.3 (1)	63 (3)	21.2 (11)	24.3 (8)	32.1 (5)	101.8 (4)	69.1 (8)	79.3 (6)
2	3.2	3.21	2.63	2.54	0.74	0.65	1.15	22.9 (9)	92 (9)	23.0 (8)	32.8 (6)	30.0 (13)	103.3 (11)	69.5 (10)	79.5 (7)
3	1.5	–	–	1.21	0.48	0.74	2.41	20.1 (3)	40 (1)	22.3 (9)	–	36.0 (3)	100.6 (1)	67.6 (1)	77.5 (1)
5a	3.2	3.00	2.53	2.69	0.63	0.48	1.27	21.1 (5)	70 (7)	21.6 (10)	35.2 (3)	32.0 (6)	102.5 (6)	71.1 (12)	77.6 (2)
5b	3.2	–	–	2.96	1.18	1.05	1.31	27.5 (12)	111 (12)	30.6 (2)	42.7 (1)	30.2 (10)	105.6 (13)	72.0 (13)	82.4 (12)
6	1.9	2.16	1.89	1.94	0.64	0.52	1.33	21.9 (8)	69 (6)	19.5 (13)	34.1 (5)	30.2 (10)	102.3 (5)	68.4 (6)	78.7 (3)
7	6.4	–	–	3.61	0.86	0.84	0.73	31.6 (13)	139 (13)	29.4 (3)	–	30.1 (12)	101.5 (2)	68.1 (5)	79.1 (5)
8	6.4	–	–	5.26	0.99	1.40	0.75	17.9 (2)	106 (11)	36.4 (1)	–	36.5 (2)	102.5 (6)	68.0 (4)	78.3 (4)
9	3.2	3.11	2.68	2.08	0.58	0.59	1.57	20.5 (4)	55 (2)	24.0 (4)	–	30.6 (8)	102.7 (9)	67.7 (2)	80.7 (10)
10	3.2	3.06	2.50	2.11	0.70	0.71	1.45	25.7 (11)	67 (5)	23.8 (5)	37.2 (2)	39.2 (1)	102.8 (10)	68.8 (7)	81.2 (11)
11	3.2	–	–	2.83	0.62	0.50	1.08	25.6 (10)	101 (10)	20.5 (12)	35.2 (3)	32.7 (4)	104.2 (12)	69.3 (9)	80.3 (9)
12	3.2	3.00	2.63	2.37	0.47	0.66	1.42	21.4 (7)	64 (4)	23.8 (5)	28.7 (7)	31.9 (7)	102.5 (6)	67.8 (3)	80.1 (8)

1 in. = 25.4 mm   1 in./mi = 15.78 mm/km

- Grinding versus Longitudinal Tining—Diamond-ground sections in Colorado (US 287 [untrafficked]) and Kansas have resulted in lower levels of friction and interior noise regardless of the texture depth than the longitudinally tined sections. Near-field noise levels for the ground sections have ranged from considerably lower to slightly higher than the tined sections.
- Grooving versus Longitudinal Tining—Colorado I-70 and US 287 (untrafficked) sections showed a slight increase in texture depth of grooved textures resulting in similar to lower levels of friction, slightly lower interior noise, and slightly lower to slightly higher near-field noise.
- Turf, Broom, and Burlap Drags—These textures will incur friction problems and may develop noise issues, if high texture is not provided and/or high-quality aggregate is not used. If studded tires are not used, drag textures generally provide the lowest texture deterioration rates under traffic, and possibly under snowplows.
- Effect of Smoothness on Noise—Most sections exhibited high or moderately high levels of smoothness (IRI less than 90 to 100 in./mi), but the effect of roughness could not be determined.
- One longitudinal-tine section located in Iowa and transverse tine textures with two 0.5-in. (12.7-mm) spacing designs and shallow or standard depths (Iowa Section 1002 and Missouri Section 1001, respectively) and two 0.75-in. (19-mm) spacing designs with standard depths (Iowa Sections 8001 and 8002) were found to have notable tonal issues.

Texture Durability Analysis

Micro-Texture Deterioration

Figure 5-17 provides an indication of the durability of micro-texture for the different sites/locations, based on DFT(20) friction values obtained by the DF Tester in the wheelpath and lane center. Best-fit logarithmic functions were derived to determine the trends as a function of traffic (by state). Although the number and types of textures at each site are not the same, and the type(s) of aggregate used in the concrete mix were not known for all sites, the data illustrate the importance of using high-quality aggregate to maintain high levels of friction over time/traffic. For instance, in Colorado where high-silica granite was used and in Minnesota where a granite was also used, the initial average DFT(20) values were high and remained high under large amounts of traffic. Use of limestone in Kansas and Illinois, on the other hand, has resulted in greater rates of micro-texture deterioration.

Based on the available information concerning the types of aggregates that were used in the concrete at the various sites/locations, it is apparent that use of higher quality aggre-

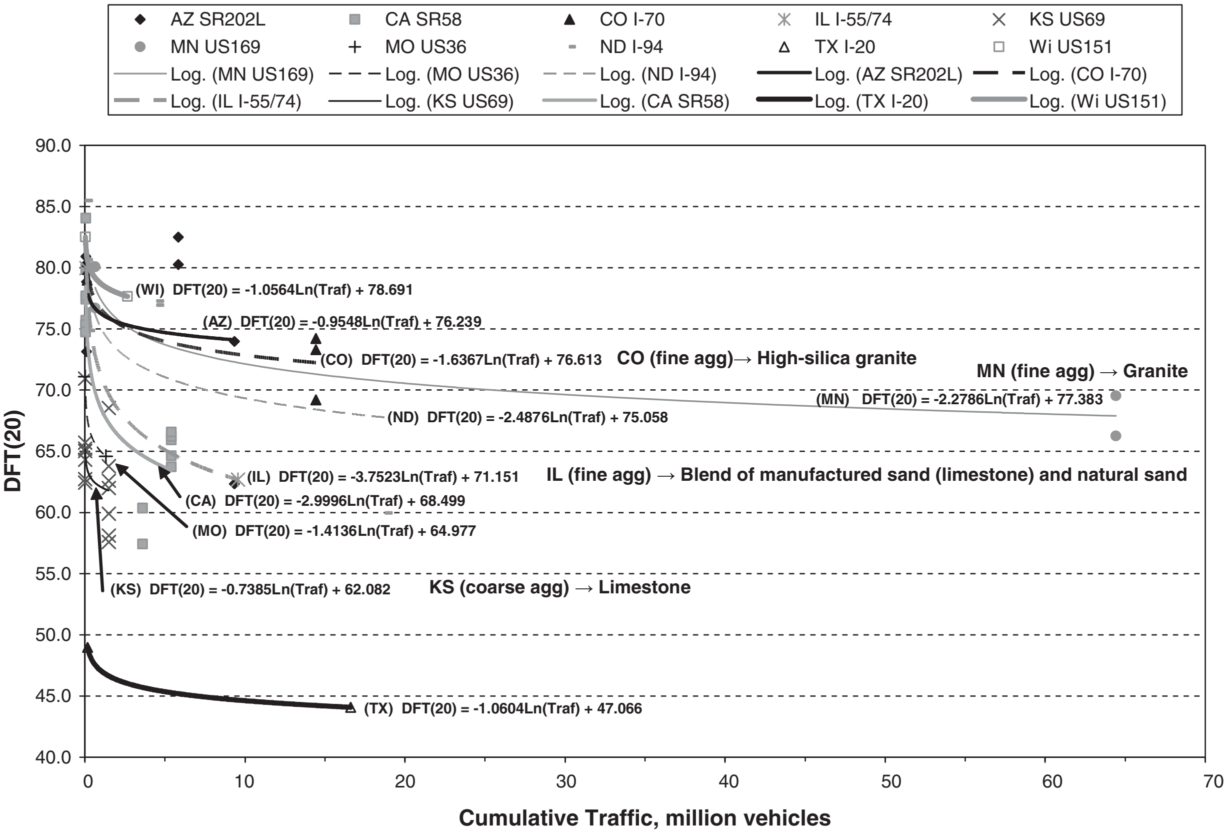


Figure 5-17. Micro-texture versus cumulative combined traffic.

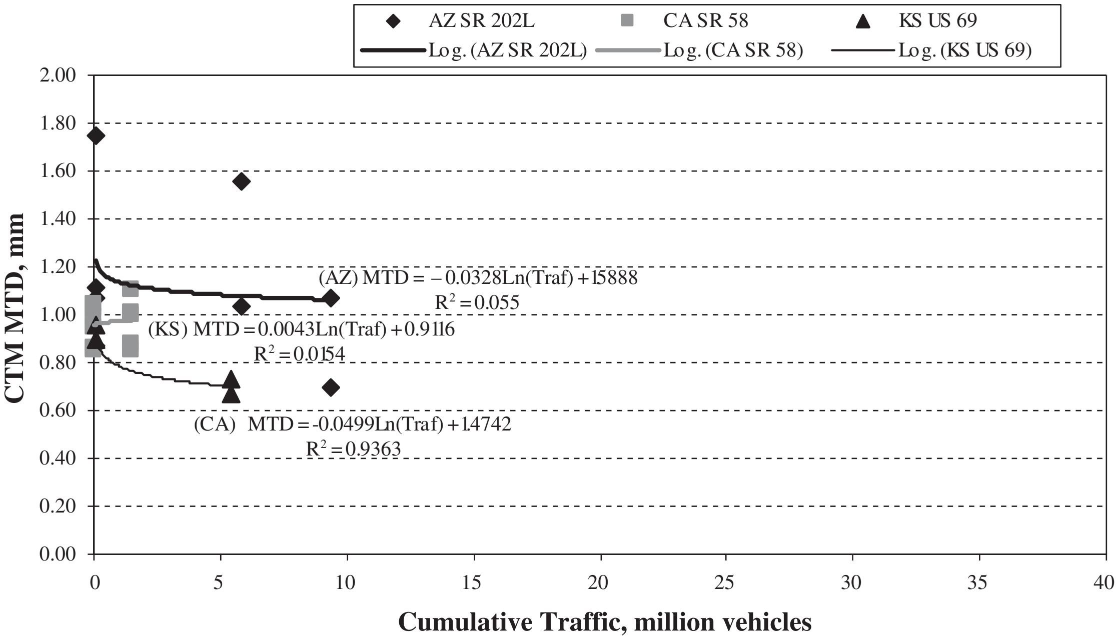


Figure 5-18. Macro-texture versus cumulative combined traffic for diamond-ground sections.

gates in the concrete mixture helps to maintain the micro-texture qualities needed for friction.

Macro-Texture Deterioration

Figures 5-18 through 5-23 show the rates of deterioration in macro-texture for the different texture types based on CT Meter MTD values (or in some cases, high-speed profiler EMTD values) taken in the wheelpath and lane center. Best-fit logarithmic functions were derived for each data set.

These figures illustrate the reduction in texture depth for each texture type. With the exception of some of the sections in Kansas, which showed greater texture depth in the wheelpath than in the lane center (possibly because of wear caused by

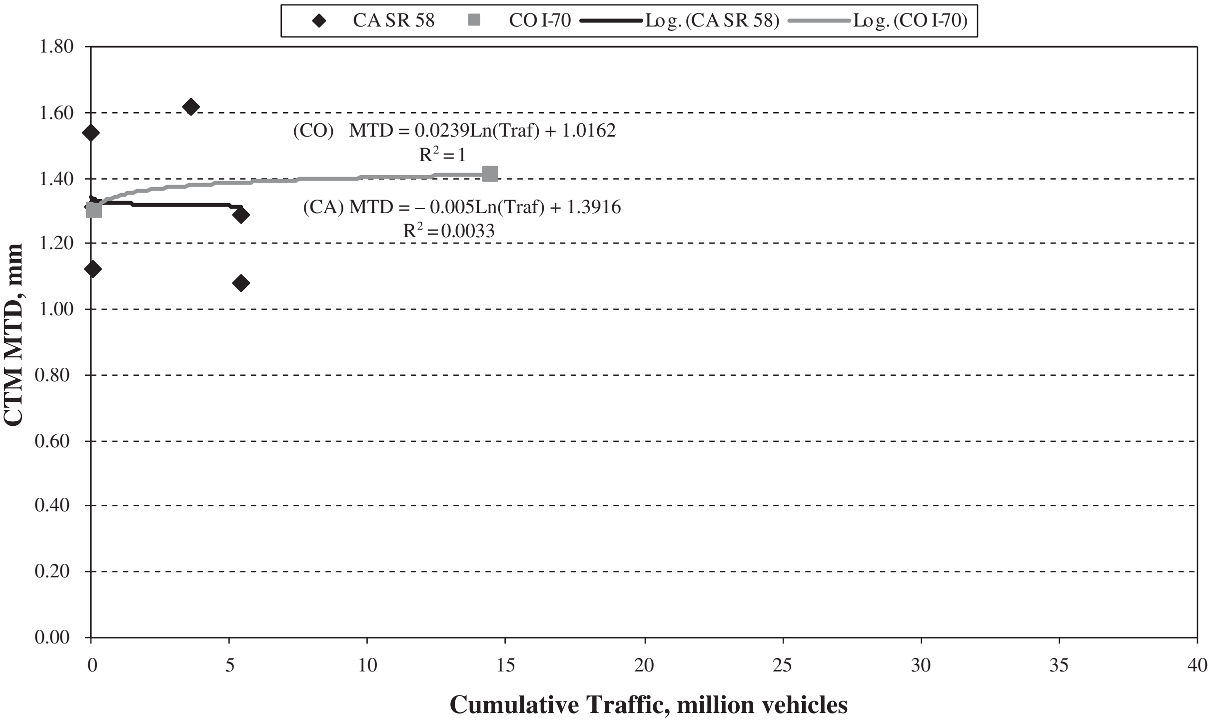


Figure 5-19. Macro-texture versus cumulative combined traffic for longitudinal grooved sections.

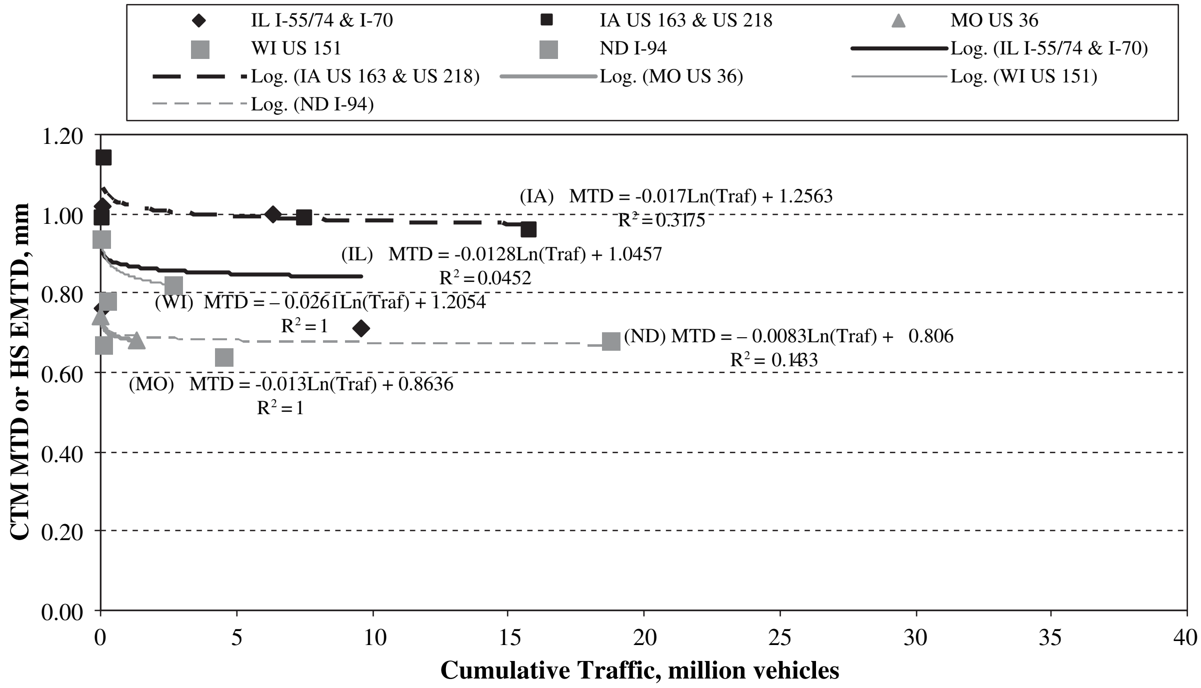


Figure 5-20. Macro-texture versus cumulative combined traffic for transverse tine sections.

snowplows in the lane center), upwards of 0.012 in. (0.3 mm) of loss over the first 10 million applications of traffic occurred. Considerably lower losses of the longitudinal and transverse tine textures (0.004 to 0.005 in. [0.1 to 0.12 mm]) were experienced. With the exception of a turf drag section in Iowa (Section 1007), the drag and the longitudinal-grooved textured sections showed only slight amounts of loss (0.002 to 0.003 in. [0.05 to 0.08 mm]).

As Figure 5-23 shows, the shotblasted section in Texas and an asphalt-surfaced section in Illinois exhibited greater texture depth in the wheelpath than in the lane center. Snowplow operations may have been a factor for the sections in Illinois

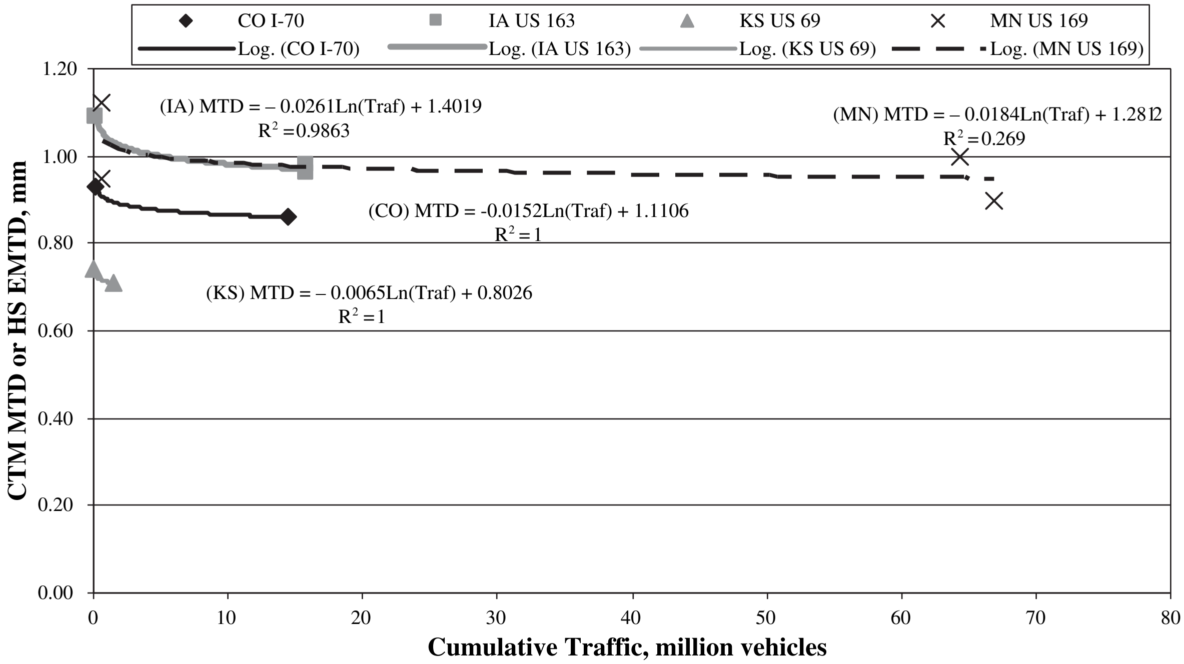


Figure 5-21. Macro-texture versus cumulative combined traffic for longitudinal-tine sections.

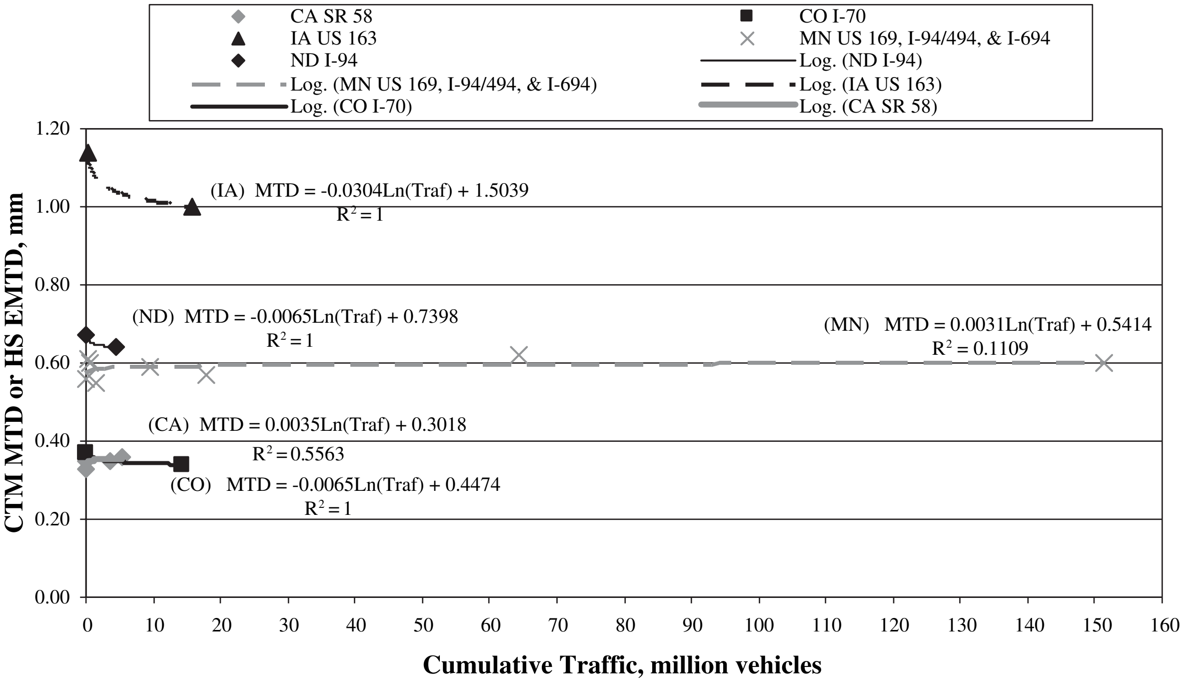


Figure 5-22. Macro-texture versus cumulative combined traffic for longitudinal drag sections.

but not for the sections in Texas. The other asphalt-surfaced textures exhibited losses between 0.002 and 0.004 in. [0.05 and 0.1 mm]) after 20 million vehicle applications; an ultra-thin bonded wearing course section in Kansas had nearly 0.008 in. (0.2 mm) loss after 2.5 million vehicle applications.

Because of the very limited number of test sections of each texture type, a time-series for MTD data could not be established and the effect of climate on texture loss could not be determined. However, locations with significant freeze-thaw cycles, frequent snowfall events (and thus frequent snowplow use) and/or considerable studded tire use are expected to experience greater texture loss; one study has confirmed this trend for diamond-ground pavements (Rao et al., 1998). In this study, test data from 36 diamond-ground pavements in

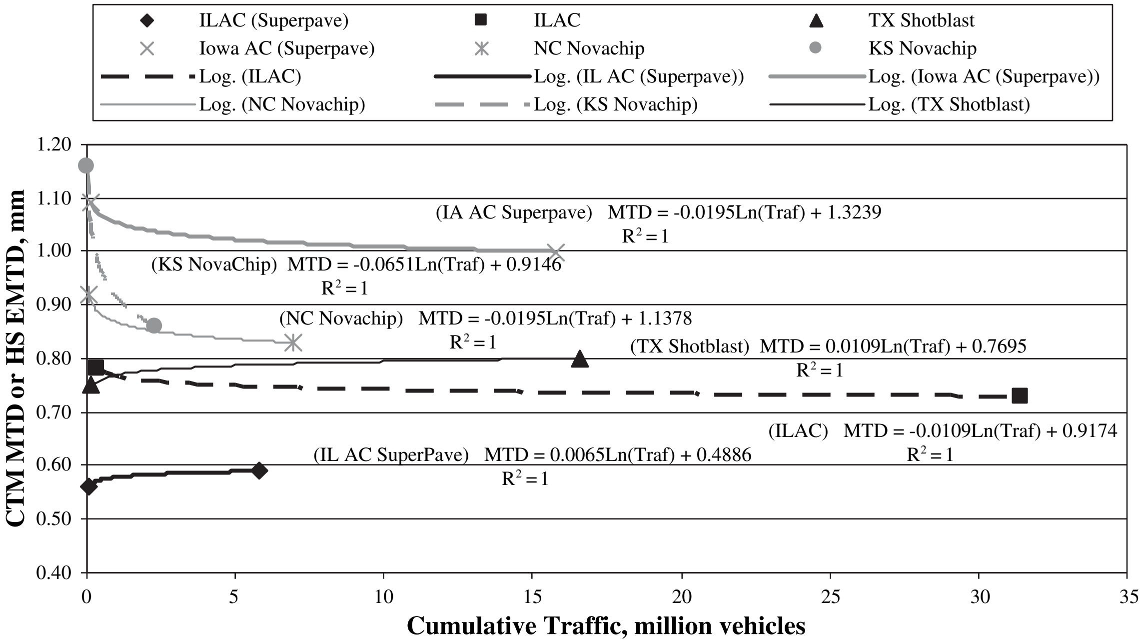


Figure 5-23. Macro-texture versus cumulative combined traffic for miscellaneous textures.

14 states were used to model texture depth over time. The resulting model showed freezing environments as a contributing factor in the deterioration of texture over time and projected a texture depth loss of 0.016 to 0.020 in. (0.4 to 0.5 mm) for nonfreezing and freezing climates, respectively, after 5 years following grinding.

In summary, the loss of macro-texture over time/traffic appears to be greatest for diamond-ground textures and lowest for longitudinally grooved and dragged textures. The geometric shape (i.e., narrow fins) of the diamond ground texture results in more substantial loss than textures with no grooves (drag textures) or those that have well-defined, widely spaced, and structurally sound grooves (longitudinal groove textures).

Noise Comparison

Noise Performance by General Texture Type

For this analysis, the 57 existing and 13 newly constructed test sections were grouped into the following seven categories based on general texture type:

- Longitudinal drag (i.e., burlap, broom, or turf).
- Transverse tine (i.e., straight, skewed, uniformly spaced, or variably spaced).
- Longitudinal tine (i.e., straight or meandering).
- Diamond ground.
- Longitudinal grooved.
- Miscellaneous textures (e.g., transverse groove, EAC, and shotblast).
- Asphalt (i.e., HMA, ultra-thin bonded wearing course).

Near-field SI and interior noise data (mean ± 1 standard deviation) for all the sections constituting each category were plotted sequentially according to the basic time at which the testing was performed for the following three basic traffic levels:

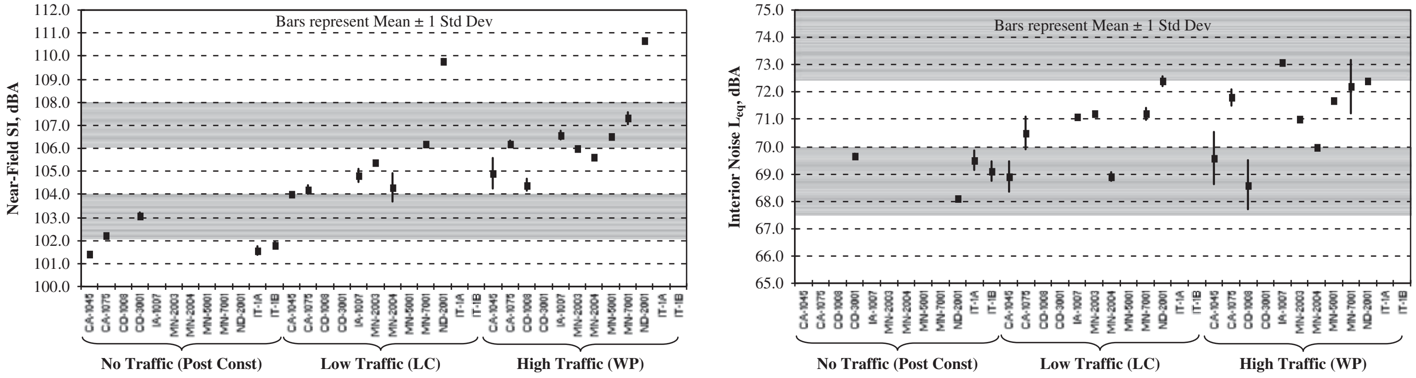
- No traffic—Post-construction testing, prior to opening of facility to traffic.
- Low traffic—Lane center test measurement, less than 5,000,000 cumulative vehicles and/or less than 500,000 cumulative trucks.
- High traffic—Wheelpath test measurement, greater than 5,000,000 cumulative vehicles and/or greater than 500,000 cumulative trucks.

Figures 5-24 through 5-30 show noise ranges that are used to qualitatively assess the noise levels exhibited by each general texture type. The noise ranges are designated as levels A through E and are defined in Table 5-13.

Although many factors (e.g., texture characteristics, climate, traffic, and pavement condition) influence the results shown in these figures, some general trends regarding the qualitative noise performance over time/traffic can be seen, as summarized in Table 5-14. The tonal whines identified previously for some of the textures (primarily transverse-tine sections) were not considered in these assessments.

Diamond-ground and grooved textures showed the lowest initial noise levels, followed by longitudinal drag, longitudinal-tine, and transverse-tine textures. Asphalt surfaces exhibited the lowest long-term noise, followed closely by the diamond-ground and grooved textures and longitudinal tining. EAC, shotblasted PCC, and transverse grooving exhibited the highest long-term noise.

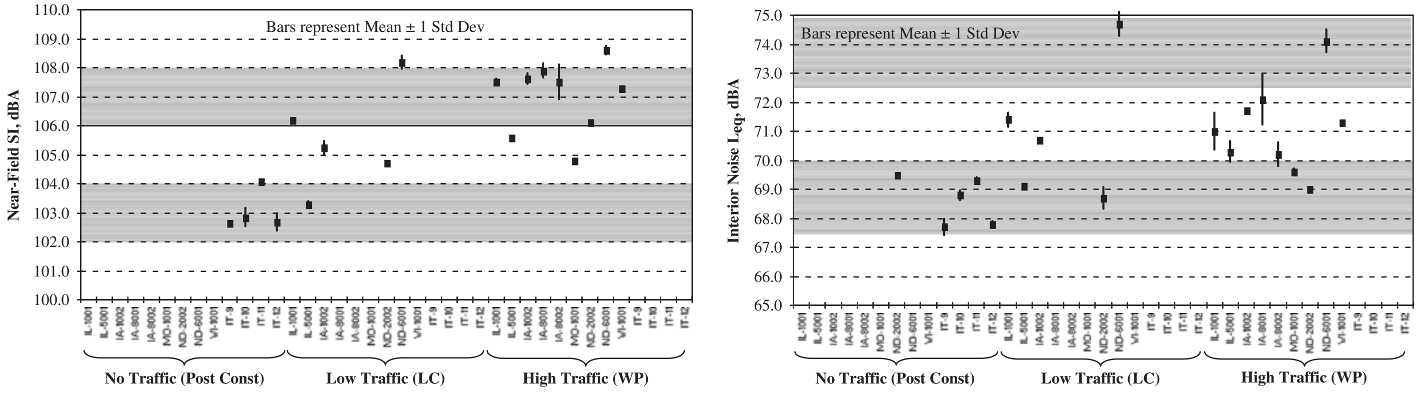
Most sections showed an increase in noise, but some showed virtually no change in noise over time/traffic (i.e., lane center versus wheelpath measurements). These noise increases occurred despite reductions in texture depth, probably because of changes in texture orientation and spectral makeup,



(a) Near-Field Noise

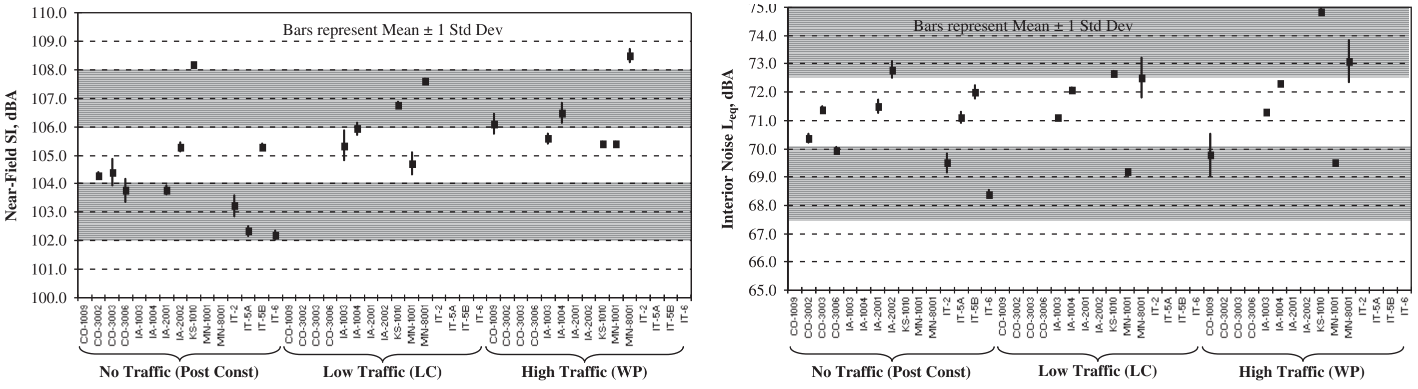
(b) Interior Noise

Figure 5-24. Noise levels for longitudinal drag textures.



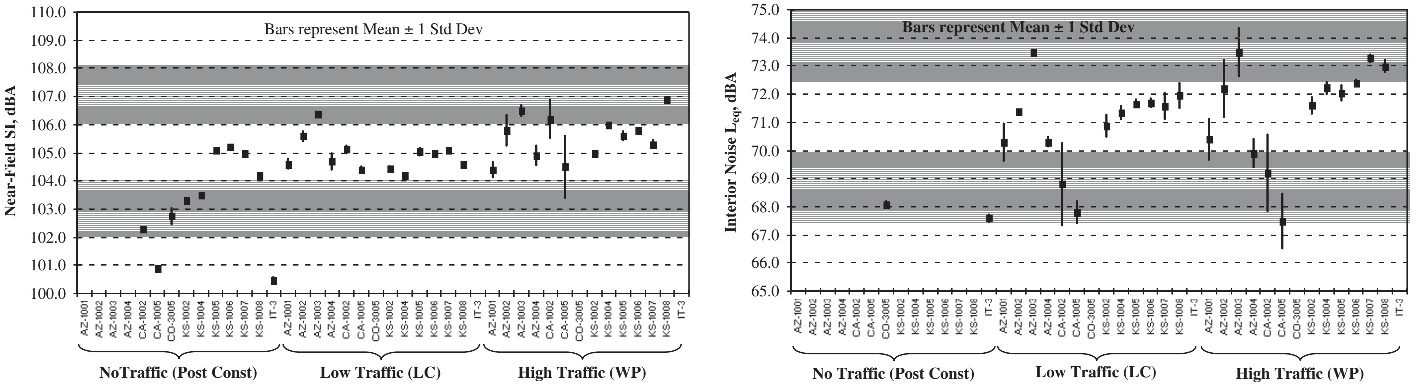
(a) Near-Field Noise (b) Interior Noise

Figure 5-25. Noise levels for transverse tine textures.



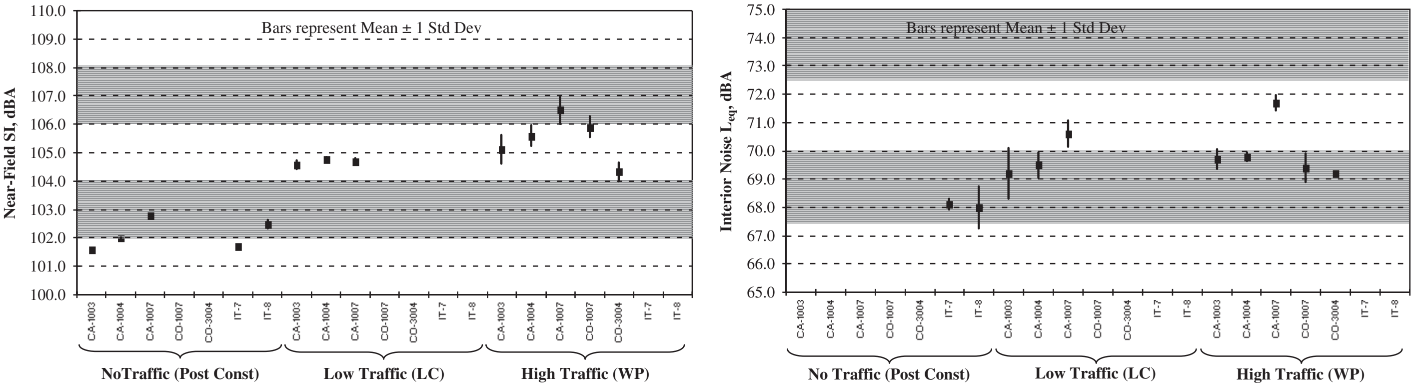
(a) Near-Field Noise (b) Interior Noise

Figure 5-26. Noise levels for longitudinal-tine textures.



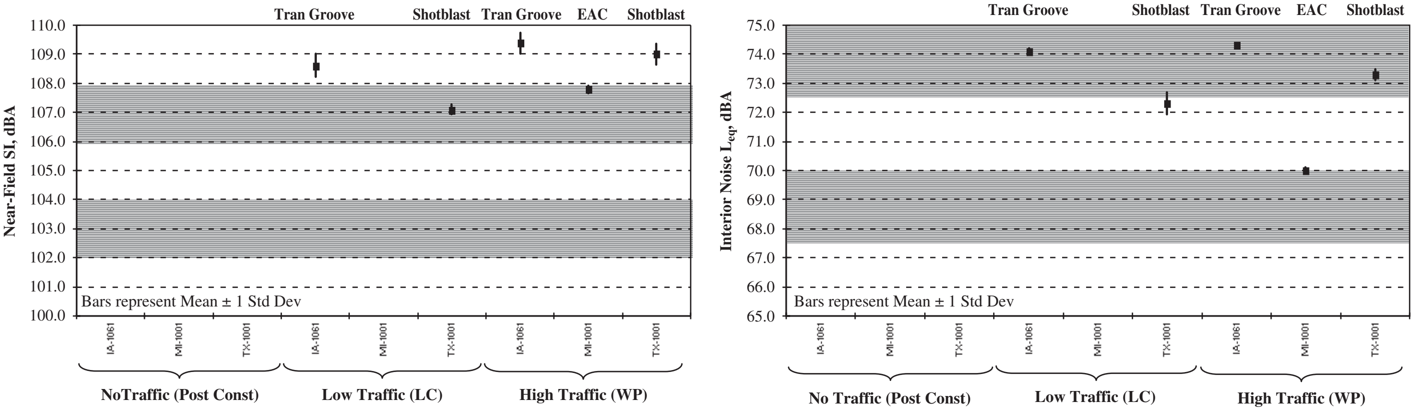
(a) Near-Field Noise (b) Interior Noise

Figure 5-27. Noise levels for diamond-ground textures.



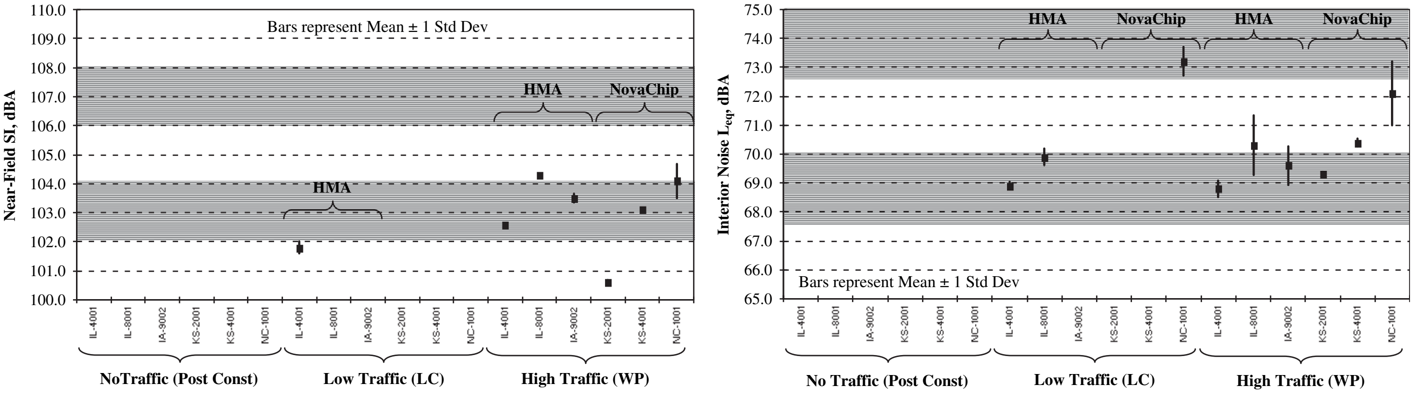
(a) Near-Field Noise (b) Interior Noise

Figure 5-28. Noise levels for longitudinal grooved textures.



(a) Near-Field Noise (b) Interior Noise

Figure 5-29. Noise levels for miscellaneous textures.



(a) Near-Field Noise (b) Interior Noise

Figure 5-30. Noise levels for asphalt surface textures.

Table 5-13. Noise ranges for qualitative assessment of noise.

Noise Level	Description	Near-Field SI Range, dB(A)	Interior L_{eq} Range, dB(A)
A	Low	< 102.0	< 67.5
B	Fairly Low	102.0 to 104.0	67.5 to 70.0
C	Moderate	104.0 to 106.0	70.0 to 72.5
D	Fairly High	106.0 to 108.0	72.5 to 75.0
E	High	> 108.0	>75.0

Table 5-14. Qualitative noise level performance trends for different textures.

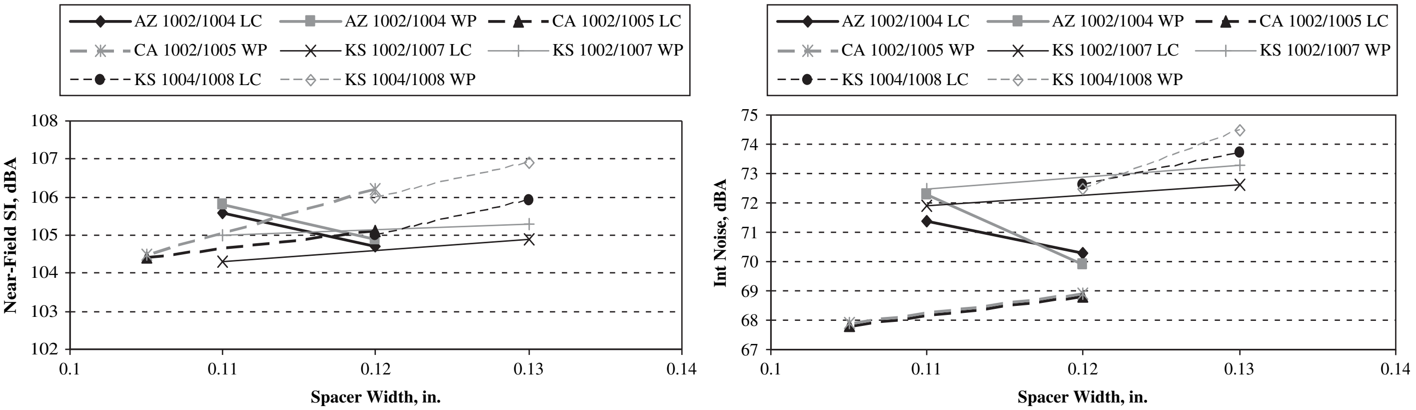
Texture Category	Near-Field SI Noise Level		Interior L_{eq} Noise Level	
	Initial	Long-Term	Initial	Long-Term
Long Drag	B	D	B	C
Tran Tine	B	D	B	C
Long Tine	B/C	C/D	B/C	C
Long DG	A/B/C	C	A/B	B/C
Long Groove	A/B	C	A/B	B/C
Misc. PCC	–	D/E	–	C/D
Asphalt	–	B	–	B/C

increased distress and/or roughness, or increased joint/joint seal degradation.

Effect of Texture Dimensions on Noise Performance

With several texture designs included in each of the seven texture categories, the following effects of texture dimensions (e.g., groove spacing and depth) on near-field SI and interior L_{eq} noise were observed:

- Diamond Grind
  - Effect of spacer widths—Conflicting results were observed. For example, sections in Arizona showed lower noise and friction associated with wider spacings, and sections in California and Kansas indicated the opposite (see Figure 5-31). In all cases, however, the texture with the lower texture depth produced lower noise.
- Longitudinal Groove
  - Effect of groove spacing—Data from California indicated that increased spacing (0.75 in. versus 0.375 in. [19 mm versus 9.5 mm]) results in lower interior noise and slightly lower near-field noise.
  - Effect of groove depth—Data from California indicated that increased depth (0.25 in. versus 0.125 in. [6.4 mm versus 3.2 mm]) results in greater near-field and interior noise.
- Longitudinal Tine
  - Effect of tine depth—Data from Colorado indicated that increased depth (0.1875 in. versus 0.125 in. [4.8 mm versus 3.2 mm]) results in greater near-field and interior



(a) Near-Field Noise

(b) Interior Noise

Figure 5-31. Effect of diamond grind spacer width on noise.

noise. Data from the Illinois Tollway showed similar results, with standard-depth (0.125 in. [3.2 mm]) tines producing greater noise than shallow-depth (0.075 in. [2 mm]) tines.

- Longitudinal Drag
  - Drag type—Despite similar texture depths, a broom drag in California produced greater near-field and interior noise than burlap drag.

Relationship of Near-Field Noise with Interior Noise and Pass-By Noise

Figure 5-32 is a plot of near-field SI noise and interior L_{eq} noise for the 70 test sections (57 existing and 13 newly constructed sections). The data shown are the average values of repeated runs made in the wheelpath and lane center positions of each test section. A linear trend-line through the data shows a general relationship ($R^2 = 0.51$) between the two noise sources and one that somewhat reflects the qualitative noise levels for the five ranges of SI. The interior L_{eq} values in Figure 5-32 are all within 3% of the values established previously in Table 5-13.

Figure 5-33 is a plot of near-field SI noise versus far-field CPB noise in which most of the data points are for measurements taken on the newly constructed test sections. A linear trend-line through these data shows a general relationship ($R^2 = 0.51$) between the two non-equal noise types.

The interior noise is influenced by the physical properties of the test vehicle and tires, which determine the type and degree of dampening or attenuation that takes place on the various noise frequencies produced at the source. Pass-by noise, however, may be influenced by the conditions at the time of testing (e.g., wind speed and direction, barometric pressure, and other site characteristics).

Statistical Analyses

Texture Depth Measurement Procedure

During field testing, a difference was observed between texture depth measured by the high-speed profiler and that measured by the CT Meter. This difference could be attributed to the difference in sampling and collecting the data, transforming the raw data into the MPD statistic, and converting MPD into EMTD (high-speed profiler) or MTD (CT Meter).

The high-speed profiler uses a laser to measure the elevation profile (sampling/recording interval = 1 point every 0.016 in. [0.4 mm]) along the length of a section at a distinct position within a lane (e.g., wheelpath or lane center). The CT Meter uses a laser to measure the circular elevation profiles (radius = 11.2 in. [284 mm]) at individual spots selected along the length of a section. Thus, the high-speed elevation profile represents a continuous set of measurements taken in a virtual straight line (longitudinal), whereas the CT Meter elevation profile represents one discrete set of measurements taken across the horizontal plane (longitudinal and transverse). Multiple test locations are required by the CT Meter to give a more accurate indication of the texture depth along the length of the section.

Texture depth data for both the existing and the newly constructed sections were compiled and statistically analyzed to

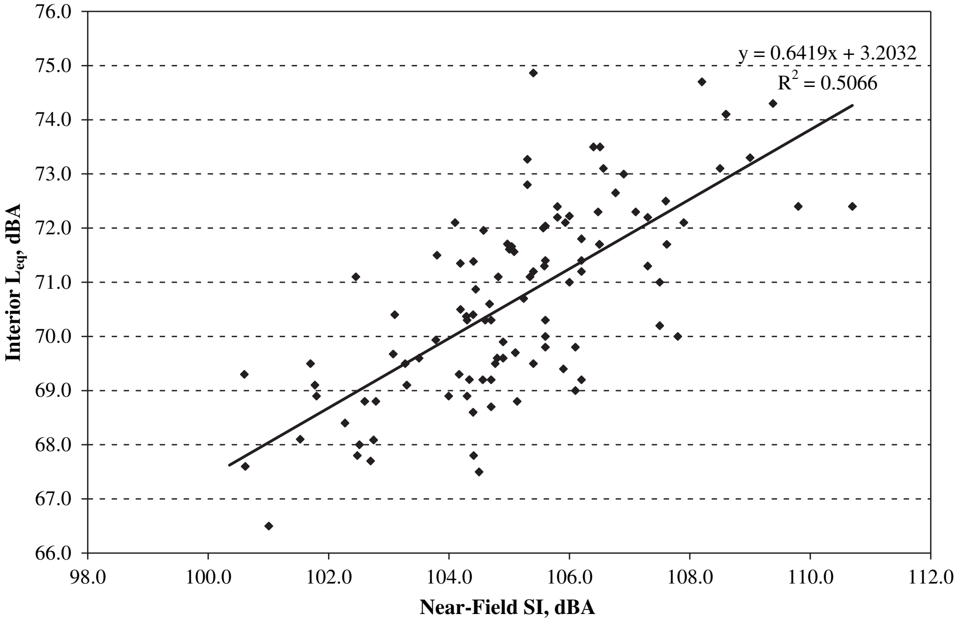


Figure 5-32. Near-field noise versus interior noise.

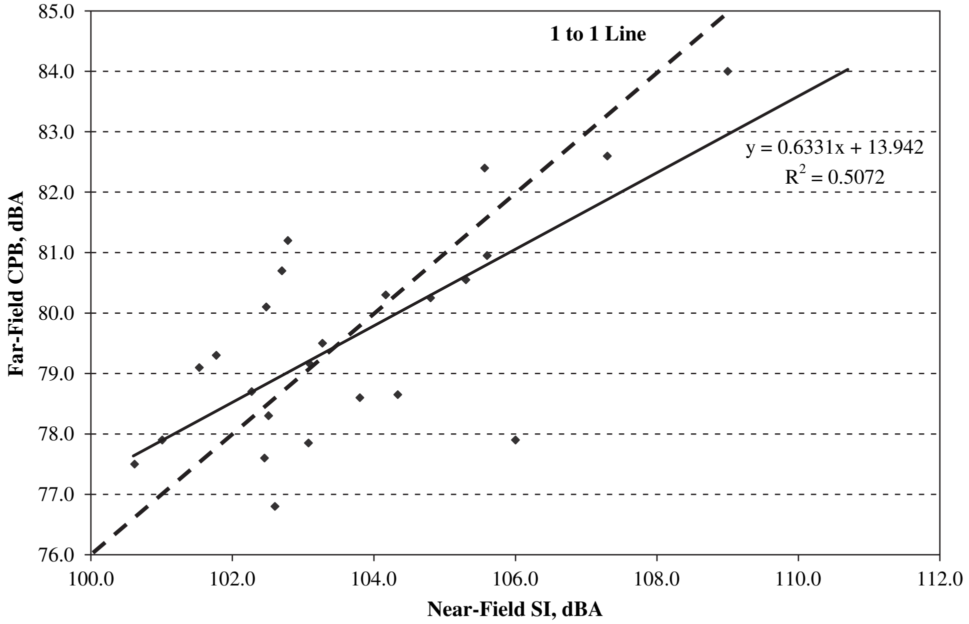
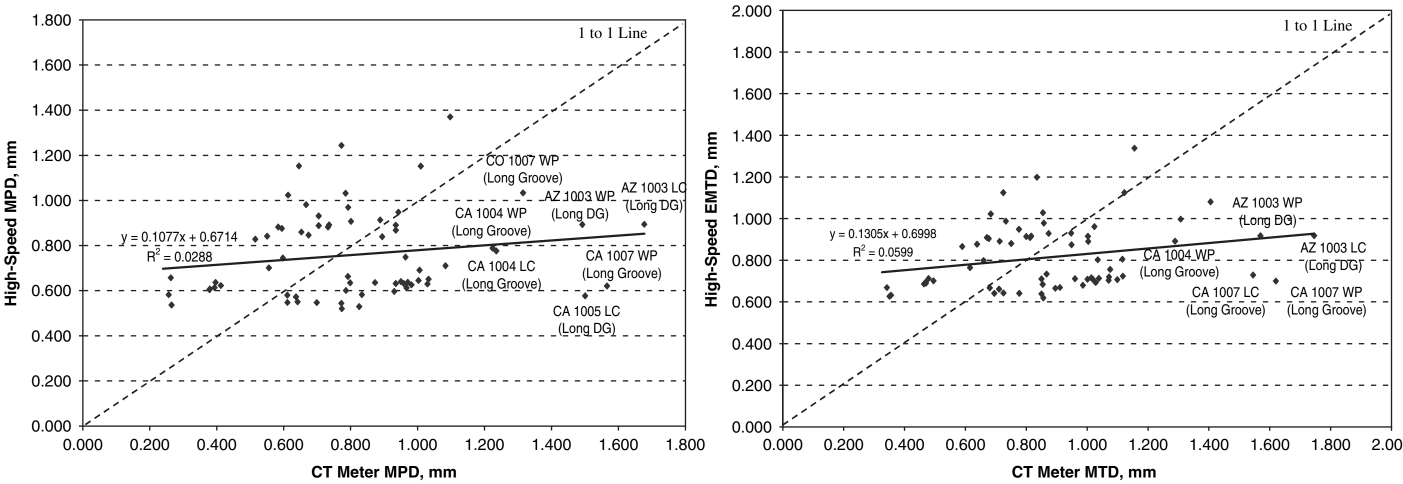


Figure 5-33. Near-field noise versus far-field CPB noise.

determine the extent of agreement between the two methods of measurement. Figure 5-34 compares high-speed MPD and CT Meter MPD and high-speed EMTD and CT Meter MTD. The high-speed data shown are the mean values of three runs at a particular position (i.e., wheelpath, lane center) for each texture test section. The CT Meter data are the mean values of 15 test locations at a particular position for each test section. No specific relationship exists between the two methods. While the difference in sampling rates is likely a factor, the texture type and direction are more profound factors. Because of their same basic direction as the path of high-speed profiler texture measurement, longitudinal textures (particularly those that are cut instead of formed) create greater difficulties in measuring texture depth—the moving laser tends to stay within a longitudinal groove or atop a longitudinal ridge for extended distances. As Figure 5-34 shows, the data points for the longitudinally grooved or ground sections are far to the right of the equality line, and the CT Meter texture depth readings for these sections are nearly twice those obtained by the high-speed profiler.

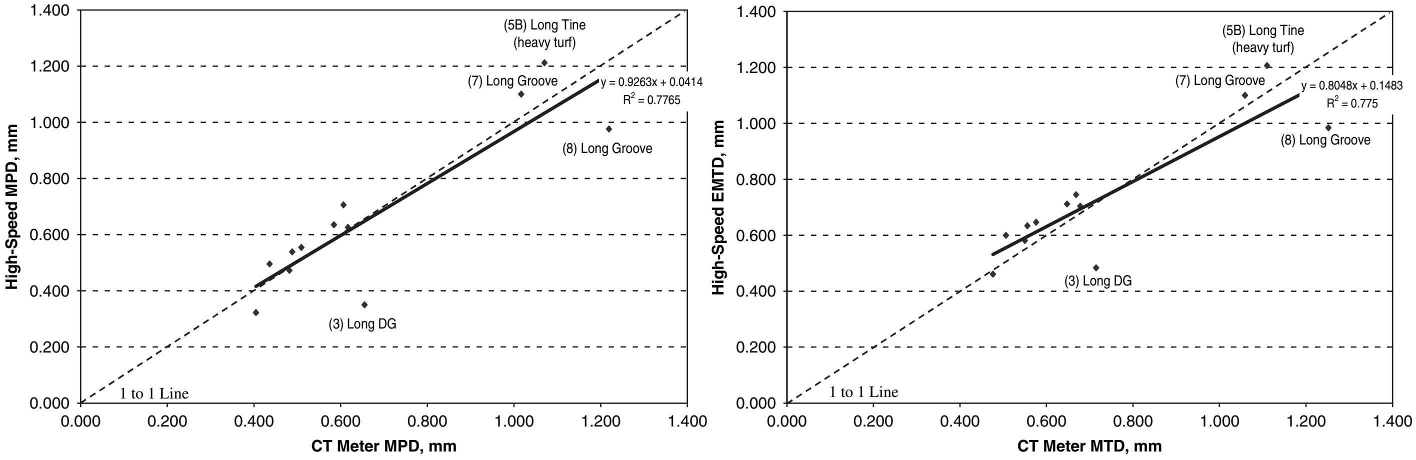
Figure 5-35 shows the texture depth data for the newly constructed test sections. Clear relationships exist, but they are affected by type and direction of texture. The diamond-ground section and one of the two longitudinal-groove sections provided substantially lower high-speed profiler texture depth readings.



(a) Mean Profile Depth

(b) Mean Texture Depth

Figure 5-34. Texture depths for existing test sections.



(a) Mean Profile Depth

(b) Mean Texture Depth

Figure 5-35. Texture depths for newly constructed test sections.

Statistical analysis (SAS Proc CORR procedure) of the texture depth data was performed to further examine the correlation between the two methods. Analysis of the immediate measure (MPD) and the extrapolated measure (MTD) showed weak correlation among the existing test sections and fairly strong correlation among the newly constructed test sections (correlation coefficients of 0.24 and 0.86, respectively). In both cases, significantly higher correlations would result if longitudinal diamond-ground and grooved sections were excluded from the analysis.

Test Site/Location Performance Analysis

The SAS Mixed Procedure was used to evaluate the performance characteristics of the test sections at individual sites/locations, including texture depth (CT Meter MPD and MTD), texture orientation parameters (CT Meter RMS and TR), near-field noise (SI), micro-texture friction (DFT(20)), and locked-wheel friction (newly constructed sections only). In each case, the null hypotheses (H_0) of (a) all textures being equal and (b) the test positions (lane center versus wheelpath) are equal, were tested. Statistical rankings using the Tukey Least Significant Differences (LSD) method then were developed.

Existing Texture Test Sections

Table 5-15 shows the Tukey rankings for each performance variable for the existing test sections. In most cases, statistically significant differences between texture types within a test site/location were identified for each performance variable. With the exception of the Colorado US 287 site where only wheelpath measurements were taken, statistically significant differences existed between the wheelpath and lane center measurements, indicating the effects of traffic wear.

Newly Constructed Texture Test Sections

Table 5-16 shows the Tukey rankings for each of the performance variables for the newly constructed sections. For each performance variable, statistically significant differences existed among the various texture types. Also, the effect of test position (i.e., lane center versus wheelpath) on each performance variable was not statistically significant. The interactive effect of texture type and test position was statistically significant in most cases, largely due to one or two cases where statistical differences in test position were found to exist for a given texture.

Analysis of Texture, Friction, and Noise

In this analysis, the texture, friction, and noise measurements collected for the 57 existing test sections and 13 newly constructed test sections were combined with other pertinent available test section data. The texture, friction, and noise data included results from replicate tests using the high-speed texture profiler (MPD and EMTD), the CT Meter (MPD, MTD, RMS, and TR), the DF Tester (DFT(20) and extrapolated F(60)), locked-wheel friction tester (FN40 and extrapolated F(60)), and noise-testing equipment (near-field SI and interior L_{eq}). The other pertinent data included

- Age/Traffic
  - Pavement age at time of testing.
  - Estimated cumulative overall traffic at time of testing.
  - Estimated cumulative truck traffic at time of testing.
- Climate
  - LTPP climatic zone (WF, DF, WNF, DNF).
  - Average annual precipitation (AvgPrecip).
  - Average annual snowfall (AvgSnow).

Table 5-15. Tukey rankings for existing test sections.

		TEXTURE DEPTH							TEXTURE ORIENTATION										FRICTION					NOISE				
SECT ID	TEXTURE DESCRIPTION	Avg CTM MPD, mm	Avg CTM MTD, mm	Tukey Rank					Avg CTM RMS	Tukey Rank				Avg CTM TR	Tukey Rank				Avg DFT(20)	Tukey Rank				Avg SI, dB(A)	Tukey Rank			
AZ-1001	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers)	0.99	1.06		2				0.43		2			2.30	1				80.5	1				104.5	1			
AZ-1002	Long DG (jacks), 0.235-in. spacing (0.11-in. spacers)	1.01	1.09		2				0.43		2			2.34	1				77.0	1	2			105.7	1	2		
AZ-1003	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers)	1.58	1.65	1					0.64	1				2.45	1				81.0	1				106.35		2		
AZ-1004	Long DG (jacks), 0.245-in. spacing (0.12-in. spacers)	0.70	0.78			3			0.41		2			1.73		2			67.5			3		104.8	1			
CA-1002	Long DG (no jacks) 0.245-in. spacing (0.12-in. spacers)	0.74	0.81				4		0.39			3		1.87	1				72.0	1				105.65		2		
CA-1003	Long Groove (0.75-in. spacing, 0.125-in. depth), burlap drag	1.04	1.10			3			1.48		2			0.72			3		71.5	1	2	3		104.8		2		
CA-1004	Long Groove (0.75-in. spacing, 0.25-in. depth), burlap drag	1.23	1.30		2				2.16	1				0.54				4	73.0	1	2			105.25		2		
CA-1045	Long Burlap Drag	0.27	0.35					5	0.16			3		1.70		2			71.5	1	2	3		104.45	1			
CA-1005	Long DG (no jacks), 0.23-in. spacing (0.105-in. spacers)	0.73	0.81				4		0.40			3		1.83	1	2			68.5	1	2	3		104.45	1			
CA-1007	Long Groove (0.375-in. spacing, 0.25-in. depth), broom drag	1.53	1.58	1					1.76		2			0.87			3		67.5		2	3		105.6		2		
CA-1075	Long Broom Drag	0.25	0.34					5	0.14			3		1.77	1	2			66.0			3		105.25		2		
CO-1007	Long Groove (0.75-in. spacing, 0.125-in. depth), turf drag	1.28	1.35	1					1.38	1				0.94		2			74.5	1				105.9		2		
CO-1008	Long Turf Drag	0.27	0.36			3			0.16			3		1.70	1				75.0	1				104.4	1			
CO-1009	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	0.82	0.89		2				0.77		2			1.07		2			76.5	1				106.1		2		
CO-3001	Long Heavy Turf Drag[1]	0.81	0.88	1	2				0.43			3		1.87		2			92.0	1				103.0	1			
CO-3002	Long Tine (0.75-in. spacing, 0.1875-in. depth), no pretexture[1]	0.95	1.03	1	2				0.76	1				1.26			3		95.0	1				104.3		2		
CO-3003	Long Meander Tine (0.75-in. spacing, 0.125-in. depth), no pretexture[1]	1.01	1.08	1					0.74	1				1.36			3		92.0	1				104.4		2		
CO-3004	Long Groove (0.75-in. spacing, 0.125-in. depth), turf drag[1]	0.96	1.03	1	2				0.72	1	2			1.47			3		81.0	1				104.3		2		
CO-3005	Long DG (no jacks), 0.22-in. spacing (0.095-in. spacers)[1]	0.83	0.91	1	2				0.34			3		2.44	1				89.0	1				102.8	1			
CO-3006	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag[1]	0.73	0.81		2				0.49		2	3		1.51			3		89.0	1				103.8	1	2		
IA-1002	Tran Tine (0.5-in. spacing, 0.075-in. depth), turf drag																							106.35			3	
IA-1003	Long Tine (0.5-in. spacing, 0.075-in. depth), turf drag																							105.4	1			
IA-1004	Long Tine (0.75-in. spacing, 0.15-in. depth), turf drag																							106.1		2	3	
IA-1061	Tran Groove (1-in. spacing, 0.18- to 0.25-in. depth), turf drag																							109.0				4
IA-1007	Long Turf Drag																							105.7	1	2		
IA-2001	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	0.63	0.69	1					0.50		2			1.31	1				43.0	1				103.8	1			
IA-2002	Long Tine (0.75-in. spacing, 0.125-in. depth), burlap drag	0.70	0.75	1					0.64	1				1.13		2			38.5		2			105.3		2		
KS-1002	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers) & standard-sawed joints	0.77	0.85		2	3			0.36				4	2.15		2			60.5				4	104.65	1			
KS-1004	Long DG (no jacks), 0.245-in. spacing (0.12-in. spacers) & single-sawed joints	0.79	0.86		2	3			0.35			3	4	2.29	1				60.5			3	4	105.5		2		
KS-1005	Long DG (jacks), 0.255-in. spacing (0.13-in. spacers) & standard-sawed joints	0.95	1.01	1					0.45		2	3		2.13		2			64.0		2	3		105.3			3	
KS-1006	Long DG (jacks), 0.255-in. spacing (0.13-in. spacers) & single-sawed joints	0.97	1.03	1					0.45		2			2.13		2			62.5		2	3	4	105.4			3	
KS-1007	Long DG (no jacks), 0.255-in. spacing (0.13-in. spacers) & standard-sawed joints	0.98	1.04	1					0.44		2			2.21	1				62.5		2	3	4	105.1			3	
KS-1008	Long DG (no jacks), 0.255-in. spacing (0.13-in. spacers) & single-sawed joints	0.91	0.98	1	2				0.42		2			2.18	1				64.5		2			106.4			3	
KS-1010	Long Tine (0.75-in. spacing, 0.15-in. depth), turf drag	0.65	0.72			3			0.53	1				1.22			3		70.0	1				105.35			3	
MN-7001	Long Turf Drag	0.40	0.48		2				0.27		2			1.47	1				71.5		2			106.8	1			
MN-8001	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	0.91	0.98	1					0.82	1				1.12		2			75.0	1				108.15		2		
ND-2001	Long Heavy Turf Drag	0.57	0.65	1					0.47	1				1.22		2			78.5	1				110.3		2		
ND-2002	Tran Tine (variable spacing, 0.1-in. depth), turf drag	0.39	0.47		2				0.22		2			1.77	1				81.0	1				105.5	1			

[1] Mean values based on right wheelpath measurements only.

Shaded items indicate no data (or rankings) were available.

1 in. = 25.4 mm

Table 5-16. Tukey rankings for the newly constructed test sections.

SECT ID	TEXTURE DESCRIPTION	TEXTURE DEPTH						TEXTURE ORIENTATION																		FRICTION					
		Avg CTM MPD, mm	Avg CTM MTD, mm	Tukey Rank				Avg CTM RMS	Tukey Rank									Avg CTM TR	Tukey Rank							Avg DFT(20)	Tukey Rank				
IT-1a	Long Heavy Turf Drag							0.18								8	9									45.6	1	2	3		
IT-1b	Long Heavy Turf Drag (modified)	0.28	0.36				4	0.15									9	1.96							7	32.8					5
IT-2	Long Tine (0.75-in. spacing, 0.125-in. depth), no pretexture	0.60	0.66		2	3	4	0.55				4						1.10		2						36.5			3	4	5
IT-3	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers)	0.65	0.71		2			0.27							7	8		2.41							7	48.3	1	2			
IT-5a	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	0.51	0.58		2	3	4	0.43					5					1.19		2	3	4				33.3					5
IT-5b	Long Tine (0.75-in. spacing, 0.125-in. depth), heavy turf drag	1.02	1.06	1				0.81			3							1.25			3	4	5			42.9		2	3	4	
IT-6	Long Tine (0.75-in. spacing, 0.075-in. depth), turf drag	0.49	0.56		2	3	4	0.40					5	6				1.23			3	4	5			34.5				4	5
IT-7	Long Groove (0.75-in. spacing, 0.25-in. depth), burlap drag	1.02	1.06	1				1.37		2								0.74	1							44.9		2	3		
IT-8	Long Groove (0.75-in. spacing, 0.25-in. depth), turf drag	1.22	1.25	1				1.57	1									0.78	1							53.6	1				
IT-9	Tran Tine (0.5-in. spacing, 0.125-in. depth), burlap drag	0.48	0.55		2	3	4	0.34						6	7			1.41						6		42.5		2	3	4	
IT-10	Tran Tine (variable spacing, 0.125-in. depth), burlap drag	0.62	0.68		2	3		0.45					5					1.36					5	6		36.8			3	4	5
IT-11	Tran Tine (1.0-in. spacing, 0.125-in. depth), burlap drag	0.44	0.51			3	4	0.40					5	6				1.10		2	3					34.3				4	5
IT-12	Tran Skew Tine (variable spacing, 0.125-in. depth), turf drag	0.58	0.65		2	3	4	0.43					5					1.28				4	5	6		36.9			3	4	5

Shaded items indicate no data (or rankings) were available.
1 in. = 25.4 mm

SECT ID	TEXTURE DESCRIPTION	FRICTION							NOISE																						
		Avg FN40R	Tukey Rank			Avg FN40S	Tukey Rank		Avg SI, dB(A)	Tukey Rank								Avg Int L_{eq}, dB(A)	Tukey Rank					Avg CPB L_{max}, dB(A)	Tukey Rank						
IT-1a	Long Heavy Turf Drag	47.4		2	3				101.5		2							69.5			3										
IT-1b	Long Heavy Turf Drag (modified)	46.4		2	3	24.4		2	101.7		2	3						69.2			3			79.2		2	3	4			
IT-2	Long Tine (0.75-in. spacing, 0.125-in. depth), no pretexture	45.9			3	32.5	1	2	103.2						6			69.5			3			79.4			3	4			
IT-3	Long DG (no jacks), 0.235-in. spacing (0.11-in. spacers)	50.3		2	3				100.5	1								67.6	1					77.5	1						
IT-5a	Long Tine (0.75-in. spacing, 0.125-in. depth), turf drag	49.7		2	3	37.8	1		102.3				4					71.1				4		77.6	1						
IT-5b	Long Tine (0.75-in. spacing, 0.125-in. depth), heavy turf drag	50.2		2	3	43.4	1		105.3								8	72.1					5	82.3							7
IT-6	Long Tine (0.75-in. spacing, 0.075-in. depth), turf drag	48.2		2	3	34.0	1	2	102.2			3	4					69.7			3			78.5	1	2	3				
IT-7	Long Groove (0.75-in. spacing, 0.25-in. depth), burlap drag	47.5		2	3				101.7		2							68.1	1	2				79.1	1	2	3	4			
IT-8	Long Groove (0.75-in. spacing, 0.25-in. depth), turf drag	55.7	1	2					102.4				4	5				67.6	1					77.9		2					
IT-9	Tran Tine (0.5-in. spacing, 0.125-in. depth), burlap drag	44.7			3				102.6				4	5				67.7	1					80.7					5		
IT-10	Tran Tine (variable spacing, 0.125-in. depth), burlap drag	62.1	1			37.1	1		102.8					5	6			68.8		2	3			81.3						6	7
IT-11	Tran Tine (1.0-in. spacing, 0.125-in. depth), burlap drag	48.6		2	3	31.5	1	2	104.0							7		69.3			3			80.4				4	5		
IT-12	Tran Skew Tine (variable spacing, 0.125-in. depth), turf drag	49.2		2	3	29.0		2	102.6				4	5				69.0			3			80.0				4	5		

Shaded items indicate no data (or rankings) were available.
1 in. = 25.4 mm

  - Number days >90°F [>32°C] and number days <32°F [<0°C].
  - Freezing index (FI).
- Pavement
  - Number of joints per 1,000 ft (305 m) (#Jts).
  - Joint width (JW).
  - General pavement condition (PvtCond) (excellent, good, fair, etc.).

The SAS Proc ANOVA and REG procedures were used to determine the effect of independent variables on each of two dependent variables—DFT(20) and near-field SI. Multiple regression techniques also were used to augment the understanding of the influence of the independent variables on friction/micro-texture and noise measurements.

Micro-Texture/Friction

Using DFT(20) data from 55 of the 70 test sections (data were not available for some sections in Illinois, Iowa, Kansas, Michigan, and Minnesota), ANOVA testing was conducted to identify variables that significantly influence this micro-texture parameter. Because initial results showed conflicting indications of the effect of traffic on DFT(20) (i.e., increased DFT(20) corresponding to increased traffic), the 13 newly constructed test sections and 2 sections in Iowa that exhibited unusually low DFT(20) data were removed from analysis. Thus, data from 30 of the 70 total test sections were used. ANOVA testing indicated the following findings regarding the effects of the dependent variable DFT(20):

- Log-normal truck traffic (lnTruck)—Increased cumulative truck traffic, reduced DFT(20) values.
- CT Meter MTD—Higher DFT(20) values were measured for pavements with greater texture depth.
- Precipitation (AvgPrecip)—Lower DFT(20) values were measured for locations with higher annual average precipitation.
- Roughness—Higher DFT(20) values corresponded to increased IRI values.
- Test position—Higher DFT(20) values were obtained for lane center compared with the wheelpath position.
- General texture indicator (GTI)—Significant differences were obtained for some general texture types, particularly the substantially lower DFT(20) values for the shotblasted section in Texas.
- Texture direction (TD)—Higher DFT(20) values were obtained for transverse textures compared with both longitudinal and uniform/isotropic textures.

Multiple regression using SAS Proc REG yielded various models linking independent variables with DFT(20) the best of which had an R² of 0.85 as follows:

$$\begin{aligned}\mathrm{DFT}(20) = {} & 76.39 - 18.99 \times \mathrm{GTI}_{\mathrm{EAC}} - 5.20 \times \mathrm{GTI}_{\mathrm{LDG}} \\ & - 8.99 \times \mathrm{GTI}_{\mathrm{LGr}} - 0.34 \times \mathrm{Precip} + 0.14 \times \mathrm{Snow} \\ & - 0.47 \times \ln(\mathrm{Truck}) + 10.12 \times \mathrm{MPD}_{\mathrm{CTM}} \qquad \text{Eq. 5-1}\end{aligned}$$

where

$\mathrm{GTI}_{\mathrm{EAC}}$ = GTI for EAC texture (=1 if EAC, 0 otherwise).
$\mathrm{GTI}_{\mathrm{LDG}}$ = GTI for diamond ground texture (=1 if diamond ground, 0 otherwise).
$\mathrm{GTI}_{\mathrm{LGr}}$ = GTI for longitudinal grooved texture (=1 if longitudinal grooved, 0 otherwise).
Precip = Average annual precipitation (in.).
Snow = Average annual snowfall (in.).
Ln(Truck) = Log-normal cumulative truck applications.
$\mathrm{MPD}_{\mathrm{CTM}}$ = MPD from CT Meter (mm).

The results of the ANOVA and regression analyses highlighted the effect of traffic (e.g., truck traffic) on micro-texture, the favorable micro-texture of transverse textures over uniform and longitudinal textures, and the possible influence of macro-texture and mega-texture (roughness) on micro-texture. The relationship of climatic variables to DFT(20) could not be determined in this project.

SI Noise

Based on SI data from all 70 test sections, ANOVA testing showed a statistically significant relationship of traffic, texture depth (CT Meter MTD), and general texture type/texture direction to SI at the 95% confidence level. SI increases as texture depth and traffic increase. With respect to general texture type/texture direction, SI is primarily driven by the significant range in noise differences exhibited by asphalt-surfaced pavements at the low end and EAC at the high end. However, significant differences between grooved and ground textures and transverse-tine textures were also noted.

Multiple regression using SAS Proc REG yielded various models linking independent variables with log(SI), the best of which had an R² of 0.61 as follows:

$$\begin{aligned}\mathrm{Log}(\mathrm{SI}) = {} & -0.35 + 0.37 \times \mathrm{TD}_{\mathrm{TRAN}} + 0.62 \times \mathrm{GTI}_{\mathrm{EAC}} + 0.20 \\ & \times \mathrm{GTI}_{\mathrm{LTi}} + 0.01 \times \#\mathrm{Jts} + 0.06 \times \ln(\mathrm{Traffic}) \\ & + 0.53 \times \mathrm{MPD}_{\mathrm{HS}} \qquad \text{Eq. 5-2}\end{aligned}$$

where

$\mathrm{TD}_{\mathrm{TRAN}}$ = Transverse texture direction (=1 if transverse, 0 otherwise).
$\mathrm{GTI}_{\mathrm{EAC}}$ = GTI for EAC texture (=1 if EAC, 0 otherwise).
$\mathrm{GTI}_{\mathrm{LTi}}$ = GTI for longitudinal-tine texture (=1 if longitudinal-tine, 0 otherwise).
#Jts = Number of joints per 1,000 ft (305 m).
Ln(Traffic) = Log-normal cumulative traffic applications.
$\mathrm{MPD}_{\mathrm{HS}}$ = MPD from high-speed profiler (mm).

In this model, the key variables, aside from the EAC texture type, are texture depth, transverse texture direction, and longitudinal-tine texture type. Traffic and joints (in terms of the number/frequency of joints) also are seen as factors in this model. Thus, the ANOVA and regression analyses indicated that near-field SI noise is influenced to a large extent by texture depth (the deeper, the louder) and texture type and direction. Also, SI is increased as the number of traffic applications increased and the number/frequency of joints increased.

Noise-Texture Relationship

Near-field SI data and various texture parameter data from the 13 newly constructed test sections were used to develop a statistical model relating pavement texture and pavement–tire noise to better understand the specific texture parameters that significantly influence the generation of noise. The model was intended to establish SI as a function of one or more of the following variables:

- Texture direction (longitudinal, transverse, or uniform/isotropic).
- CT Meter MTD
- CT Meter RMS
- CT Meter TR
- Texture PSD L_4/L_{63} (derived from texture profiles from high-speed profiler)
- Texture PSD A_1/A_2 (derived from texture profiles from high-speed profiler)
- Texture PSD Peak Wavelength (PW) (derived from texture profiles from high-speed profiler)

Two sequential statistical analyses were performed. The first analysis used texture PSD parameter values representing the full test segment length, and the second analysis used discrete location values of the texture PSD parameters. For both analyses, discrete location values of SI were computed corresponding to each of the five short (6 ft [1.8 m]) segments where CT Meter tests were performed. The mid-lengths of these discrete segments were located 100, 200, 300, 400, and 500 ft (30.5, 61, 91.5, 122, and 152.5 m) from the start of each test section. All replicate test data were included in the analysis, which consisted of the SAS REG procedure. Results of the first analysis yielded the following model with an R^2 of 0.772:

$$SI = 106.63 - 14.28 \times A_1/A_2 + 2.79 \times RMS - 1.25 \times Dir \quad \text{Eq. 5-3}$$

where

Dir = 0, for transverse or uniform/isotropic texture.
= 1 for longitudinal texture.

Figure 5-36 plots the actual versus predicted SI values using this partially discrete model. The data and corresponding trend line on the left are based on actual averaged discrete location SI values. The model gives a near 1-to-1 relationship of actual and predicted SI.

The data and corresponding trend line on the right are based on actual average SI values for the full-length (528 ft [161 m]) of a test segment. While other factors influence the shift between these two trend lines, the joint slap may be a major reason for the nearly 2 dB(A) difference because the discrete locations from which discrete SI values were derived did not include the pavement joints (0.25-in. [12.7 mm] wide, 15-ft [4.6-m] spacing), but the full-length SI did include the joints.

As part of the second statistical analysis, discrete location PSD parameter data were computed using extracted texture profile data corresponding to each of the five short (6 ft [1.8 m]) segments where CT Meter tests were performed. Because of

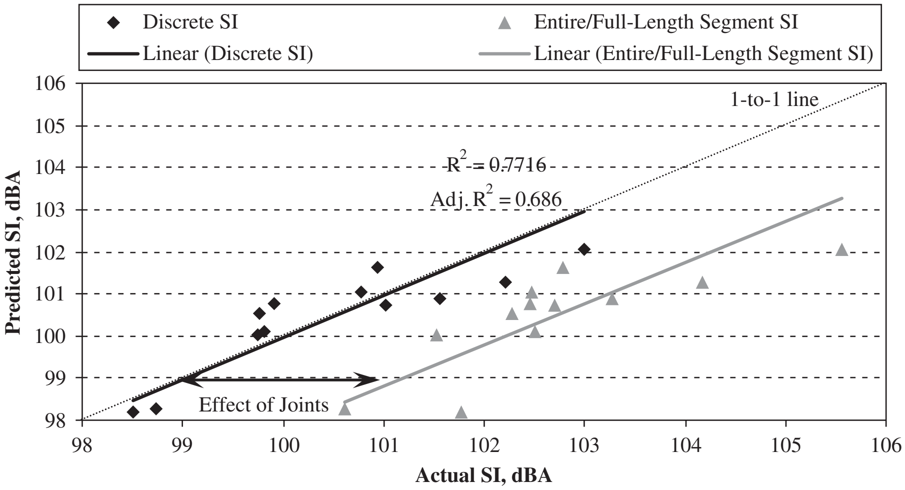


Figure 5-36. Actual versus predicted SI, based on partially discrete SI-texture model applied to full-length texture PSD parameter data.

Fourier transform requirements in MatLab®, texture profile data from a larger interval (19 ft [5.8 m]) than the 6-ft (1.8-m) CT Meter test interval was used to generate the PSD curves. With a much smaller texture profile data population than the full-length profiles, the resulting spectral curves were more variable and not as well defined.

Application of the partially discrete SI-texture model to the fully discrete data set did not produce good results. As shown in Figure 5-37, greater scatter and an over-prediction of about 1.5 dB(A) occurred as a result of differences in the A_1/A_2 PSD parameter. On average, A_1/A_2 values computed from the discrete PSD curves (i.e., the 19-ft [5.8-m] profile intervals) were about 0.15 less than those computed from the full-length PSD curves; peak spectrums for the discrete PSD curves occurred at generally higher wavelengths than those for the full-length PSD curves.

To complete the second statistical analysis, the fully discrete data set was run through SAS to determine if the partially discrete SI-texture model could be improved or if a better model could be developed. The SAS Proc CORR analysis identified A_1/A_2, L_4/L_{63}, PW, and TR as statistically significant.

While not strongly correlated, the correlation coefficients for the three PSD parameters (A_1/A_2, L_4/L_{63}, and PW) generally indicated that reducing higher wavelength texture and increasing lower wavelength texture (and subsequently shifting the peak spectrum to a lower wavelength) results in reduced noise. In the case of TR, the correlation coefficient was not strong and contradicted the expectation that a lower TR will result in lower noise. This contradiction is primarily attributed to the low noise and high TR values exhibited by the diamond-ground and heavy turf drag test sections.

Modeling with these and other variables using the SAS proc REG procedure did not produce any particularly strong and meaningful SI-texture models. The best model obtained had an R^2 of 0.58 and indicated PW and texture direction as major factors, along with TR inversely related to SI. Both analyses indicated that pavement–tire noise is affected by various texture properties, some of which are embodied by texture PSD function. The partially discrete SI-texture model was likely weakened by the fact that the texture PSD parameters were derived from two-dimensional texture profiles, instead of a three-dimensional profile from which SI noise was measured. Other variables, such as pavement porosity and stiffness and tire tread and inflation pressure, are considered to be factors in noise generation. They were not examined in this study.

Texture Construction Analyses

Nominal Versus Actual Texture

An important consideration regarding PCC surface textures designed to satisfy friction, noise, and other requirements is the assurance that the specified texture is actually constructed. Often, various factors pertaining to the PCC mixture (weather conditions; texturing equipment, and operator) are encountered during construction that prevent a contractor from achieving the desired specified texture. In addition, the level of QC/QA of the process could influence the produced texture.

As part of the construction demonstration of test sections for this study on the Illinois Tollway (I-355 South Extension), measurements were made of the depths of tine grooves at different times following construction and prior to traffic opening. A tire-tread depth gauge was used to measure the groove depths near the right wheelpath of the outside lane every 30 ft (9.2 m) or so, both immediately behind the texturing machine (while the PCC was still fresh) and a few weeks after the PCC

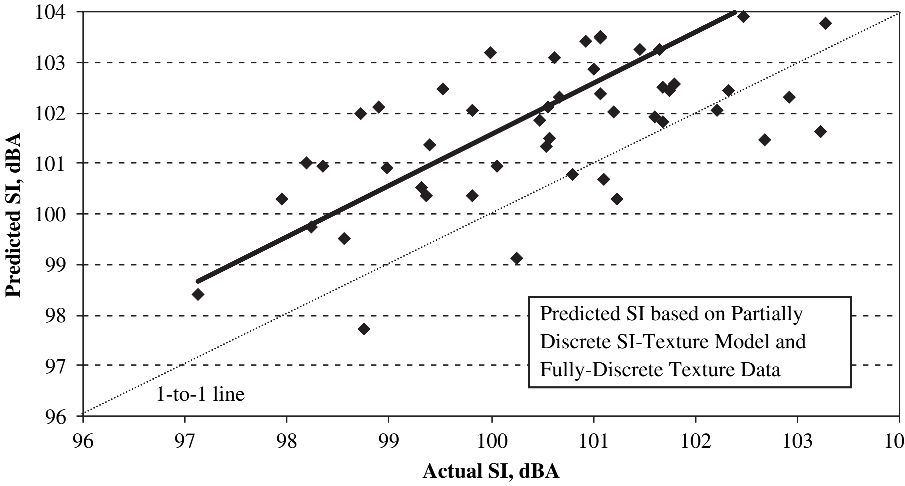


Figure 5-37. Actual versus predicted SI, based on partially discrete SI-texture model applied to discrete location texture PSD parameter data.

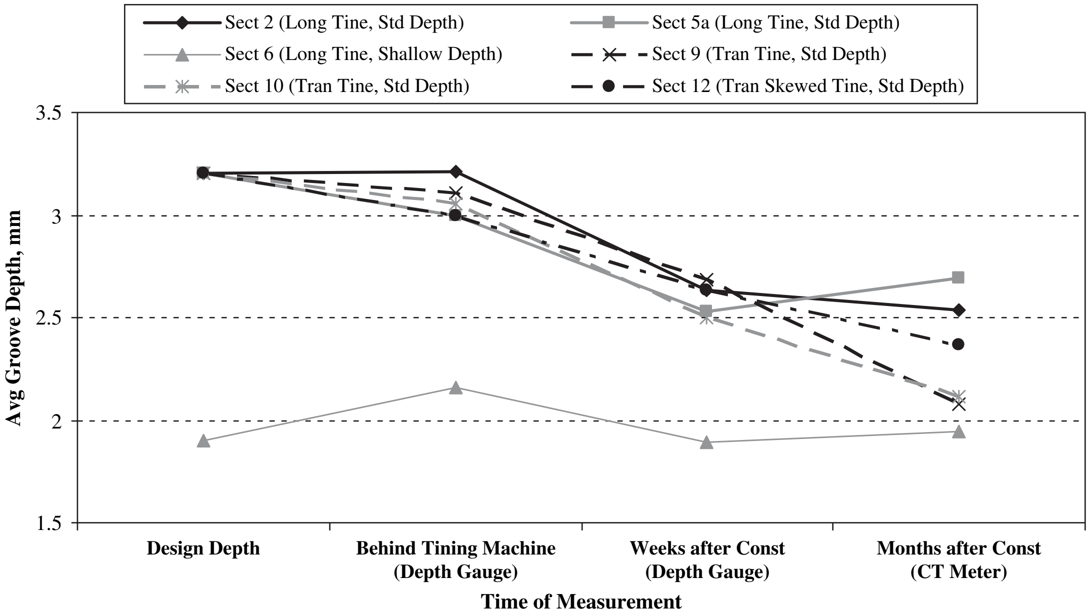


Figure 5-38. Tine depth measurements for the newly constructed longitudinal and transverse tine test sections.

had hardened. A third set of tine depth measurements was obtained from the CT Meter testing performed weeks later.

Figure 5-38 shows the average values derived from these measurements. The first set of points represent the design/specified tining depth. The measurements taken behind the tining machine were fairly close to the specified depths, but there was a marked reduction in the depth values obtained a few weeks later. CT Meter tine depth readings are of the same general magnitude, but are less consistent across textures.

Regarding the two sets of depth gauge measurements, it was noted that, despite averages being close to the specified values, a significant amount of variation in the readings was experienced for all textures, due in part to the weather conditions during construction that made it difficult for the tining machine operator to continually adjust for the conditions (both in terms of the distance maintained behind paving and finishing operations and the downward pressure applied to the tining unit).

The considerable drop in average values (on the order of 0.02 in. [0.5 mm]) between the two sets of measurements is believed to be due to the imprecision of measuring the depth of grooves. The grooves are variable and not well defined (both at the bottom and at the top, where mortar deposits lie) and measuring them in a medium that is soft and malleable (i.e., plastic concrete) and the wearing away of the mortar deposits that occurs as a result of construction traffic and any post-construction power brooming or cleaning operations affects the measured values.

The progression of texture changes illustrates the importance of evaluating/testing the texture dimensions to ensure compliance with specifications and also the need for accurate and timely measurement methods/equipment.

CHAPTER 6

Texture Selection Process

Selecting a texture for a concrete pavement requires an understanding of the particular needs and requirements of the facility and matching the friction and noise qualities of the textures to those needs (ACPA, 2000). Such needs and requirements vary substantially, because even short stretches of highway may present different features, situations, and settings that affect highway user safety and the quality of life of persons residing in the vicinity of the highway. Friction demand, for instance, is affected by factors such as traffic characteristics (i.e., speed, volume, and composition), highway alignment (i.e., vertical and horizontal), and highway geometric features affecting vehicle maneuvers (e.g., presence of turn lanes, center lanes, interchange ramps, intersections, and driveways). Similarly, highway setting (urban versus rural), right-of-way dimensions, adjacent land use (e.g., residential, commercial, agricultural), terrain, and traffic characteristics determine the need for noise abatement consideration.

When selecting a texture, it is paramount that safety, in the form of minimizing the potential for wet-weather crashes caused by inadequate friction, hydroplaning, or splash/spray, take precedence over designing for all other surface characteristics (e.g., noise, rolling resistance, tire wear, and fuel consumption).

Although speed and cross-slope are considerations for assuring safety, micro-texture and macro-texture must be controlled to improve friction and reduce the potential for hydroplaning and splash/spray. Effective micro-texture typically provides adequate surface friction on dry pavements at all speeds and on wet pavements at slower speeds, whereas macro-texture is typically required to provide adequate friction in wet conditions at high speeds (Hoerner et al., 2003). Pavement micro-texture is primarily governed by the surface properties of the aggregate particles comprising the pavement surface course, while macro-texture is determined by either the texturing method of the surface course or by the mix properties (shape, size, and gradation of aggregate) (AASHTO, 2008).

Although increased macro-texture (i.e., higher MTD) generally results in better surface drainage and thus improved friction and hysteresis, the increased size and number of asperities cause greater excitations in vehicle tires which leads to increased noise at the pavement–tire interface. Thus, trade-offs between friction and noise must be considered.

Because friction and noise are both functions of texture, and texture changes over time (depending on durability under the effects of traffic, use of snowplows, and environment), the selection process must consider both initial and long-term performance qualities. Both micro-texture (aggregate) and macro-texture (mix and texturing) durability properties are critical. Also, issues such as texture constructability and relevant agency and contractor experience are important. These factors, as well as material costs (aggregates and mixes) and texturing operational costs, all affect the cost-effectiveness of textures.

Texture Selection

A logical, rational process must be used for determining the type of texture needed for a particular highway project. Such a process involves gathering and reviewing all available critical information about the project, identifying any potential constraints/limitations (both internally and externally) in terms of available resources/technologies and performance/cost expectations, developing alternative feasible solutions, and determining the most economical and practical alternative.

Figure 6-1 illustrates the process for identifying pavement surface texturing options at the project level. This process uses key information about the project to establish target levels for friction, noise, and other surface characteristics (Step 1). The target levels are then combined with information on available (locally or otherwise) aggregate types and contractor experience with texture construction, to identify feasible texturing options (Steps 2 and 3). The cost of each texturing option (both initially and over the life-cycle of the pavement) then is estimated, and the results are evaluated carefully with respect

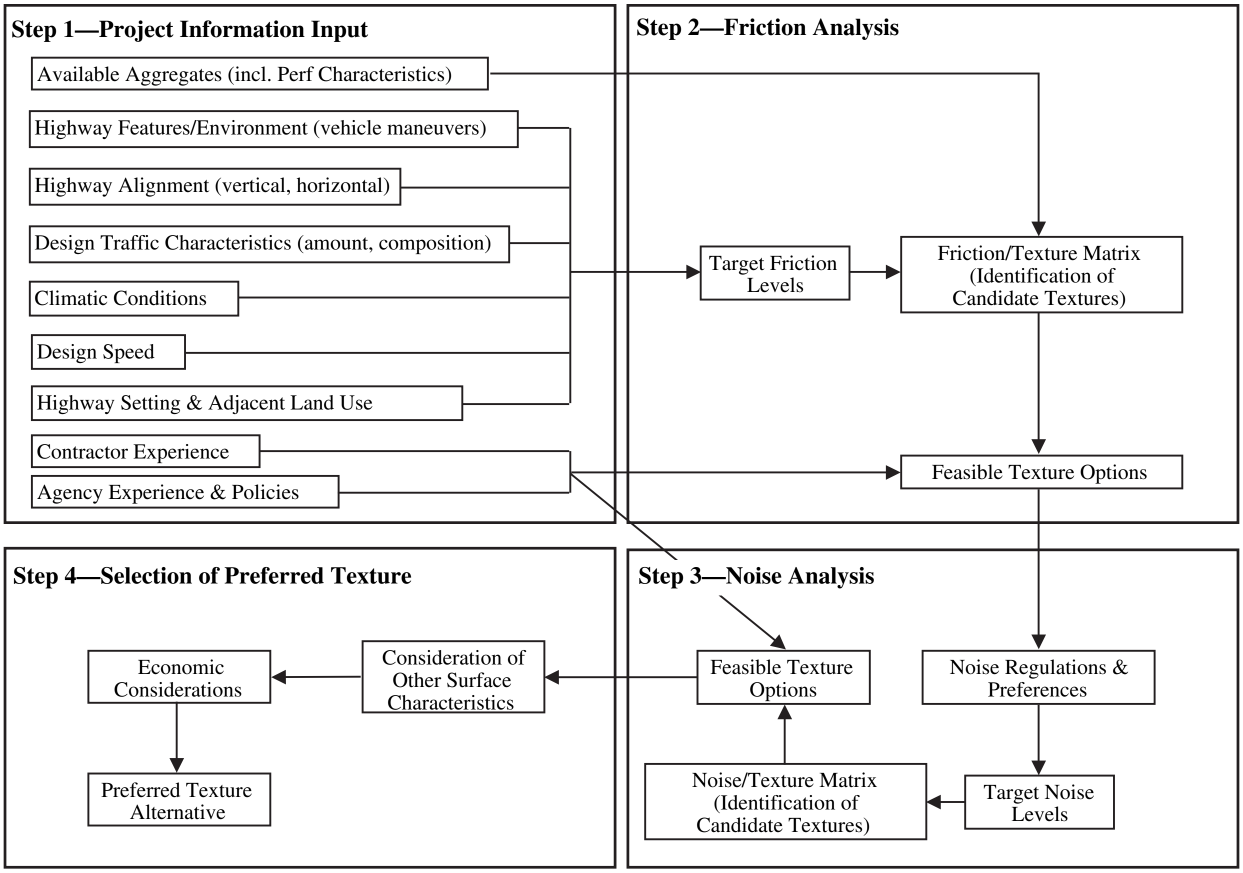


Figure 6-1. Flowchart for texture selection process.

to the overall functional and structural design and performance of the pavement (Step 4).

Steps 2 and 3 in the process cover the identification of feasible texture options, based on (1) the minimum friction levels required for safety over the life of the pavement and (2) any maximum noise levels allowed by statute (wayside noise for adjacent residents or businesses) or desired (interior noise). Information gleaned from the literature and derived from the analyses of data collected on existing test sections serves as the basis for these two steps. Friction requirements stipulated in Step 2 should conform with guidelines established and presented in the *Guide for Pavement Friction* (AASHTO, 2008).

This four-step process covers both new construction/reconstruction and rehabilitation projects. Steps 1 and 4 are essentially the same for each type of project; Steps 2 and 3 differ depending on the textures involved.

Step 1—Project Information Gathering

For each highway project, information pertaining to the needs and expectations of friction, noise, and other related surface characteristics must first be gathered. Such information includes

- Climatic Conditions—Establishing a higher threshold level of friction (and thus requiring greater amounts of texture) may be necessary for locations with increased probability of wet-weather conditions (FHWA, 2005), particularly if only polish-susceptible aggregates are available. Because wet roads have been shown to be slightly louder (1 to 4 dB(A) at the wayside) than dry roads (Sandberg and Ejsmont, 2002), consideration should be given to locations with urban settings.
- Highway Alignment—Increased friction demand associated with horizontal and vertical curves is often addressed through increases in the horizontal radius of curvature, inclusion of or increases in curve super-elevation, and/or reductions in longitudinal grades. However, the alignments for some projects (particularly, those in which the existing alignment will be kept) may preclude taking these measures. In lieu of posting reduced speed limit signs, specifying a pavement surface with increased texture depth may be a viable solution. Highway alignment, particularly the characteristics of curves, affects noise. If speed is not reduced, sharp horizontal curves will have a pronounced effect on far-field noise experienced at the interior of the curve. Also, because of the need for greater engine power emission dur-

ing uphill climbs and the likelihood of increased downhill vehicle speeds and downhill truck engine breaking, steeper grades will result in increased vehicle noise.

- Highway Features/Environment—Highway geometric features and environment influence traffic flow and thus friction. Traffic flow is defined largely by the level of interacting traffic situations (e.g., entrance/exit ramps, access drives, unsigned/unsignalized intersections), the presence of controlled (signed/signalized) intersections, the presence of specially designated lanes (e.g., separate turn lanes at intersections, center left-turn lanes, through versus traffic lanes), the presence and type of median barriers, and the setting (urban versus rural) of the roadway facility (AASHTO, 2008).
- Design Speed—The design traffic speed will influence both friction and noise. As speed increases, the level of friction decreases, reaching a minimum at approximately 60 mi/hr (96 km/hr) (FHWA, 2005). Also, as Figure 6-2 shows, pavement–tire noise and total vehicle noise increase with increasing speeds, with pavement–tire noise increasing by about 2 to 3 dB(A) per 10-mi/hr (16-km/hr) speed increase (Rasmussen et al., 2007a). At speeds above typical city speeds (>30 to 35 mi/hr [>48 to 56 km/hr]), pavement–tire noise is the dominant source in the overall noise produced by vehicles.
- Design Traffic Characteristics—Both traffic volume and composition affect friction and noise as follows:
  - The higher the traffic volume, the greater the number of driving maneuvers (per segment of highway), which increases the risk of accidents, especially in high-speed areas (NCHRP, 2009). Pavements with higher traffic volumes may require greater amounts of texture to provide a higher level of friction (FHWA, 2005). Higher traffic volumes also result in increased noise because of the additional vehicles and by a change from point source to line source noise (Rasmussen et al., 2007a).
  - Pavements with higher percentages of trucks may warrant the consideration of increased texture to account for (1) stopping distances of trucks, (2) steering capabilities of trucks, and (3) friction levels produced by truck tires (NCHRP, 2009). Because of its large propulsion system and numerous tires, the typical heavy truck is more than 10 dB(A) louder than a typical passenger car. Also, if trucks constitute more than 10% of the traffic stream, they will likely dominate the overall noise level (Rasmussen et al., 2007a).

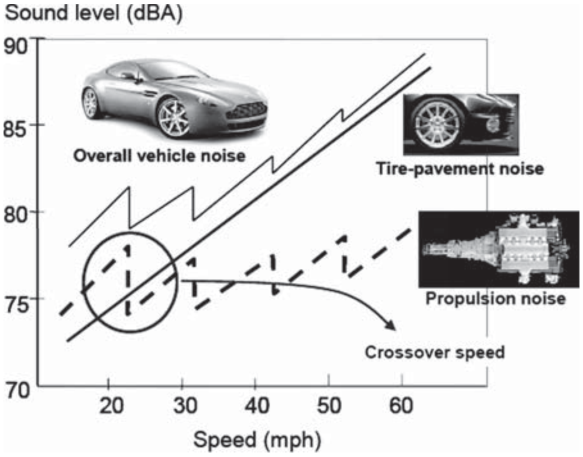


Figure 6-2. Speed effects on vehicle noise sources.

Step 2—Feasible Textures Based on Friction Requirements

With consideration of all relevant project information, an assessment can be made to determine the level of friction required over the life of the new or rehabilitated pavement and the types of textures that can provide the friction requirements. The friction design categories identified in the *Guide for Pavement Friction* (AASHTO, 2008) for individual segments with specific alignment characteristics, highway features/environment, traffic level, and travel speed can be used to define friction demands. Feasible textures for each segment or for the entire project can be identified (based on the segment with the highest overall friction demand).

Table 6-1 identifies five possible friction design categories, A through E, in which "A" represents the highest level of friction demand and "E" represents the lowest. The table can be used to establish the level of friction required for both new construction/reconstruction and rehabilitation projects.

For the selected friction design category for the project (or one for each individual segment), feasible textures can be identified by selecting combinations of micro-texture and macro-texture that will satisfy the required friction based on the IFI model (AASHTO, 2008). DFT(20) or British Pendulum Number (BPN) can be used as surrogates for micro-texture and MPD or MTD for the macro-texture component.

The micro-texture and macro-texture values should reflect long-term, residual values that account for the polishing or wearing characteristics of the aggregate and the surface material and its texturing. These characteristics include the aggregate polished DFT(20) or BPN values (known as polished stone values [PSVs]) and reduced value of MPD or MTD of the mixture, depending on the strength and durability of the mix and texture, and the anticipated environment.

The equations presented in Chapter 3 can be used to determine MPD for a required friction level F(60) and the expected long-term micro-texture friction DFT(20). MTD also can be determined based on the required friction F(60) and the expected long-term micro-texture DFT(20). Figure 6-3

Table 6-1. Friction design categories.

Degree of Driving Difficulty due to Highway Alignment Issues	Degree of Driving Difficulty due to Highway Features/ Environment	Low Traffic[1]		Moderate Traffic[1]		High Traffic[1]	
		Low/ Moderate Speed[2]	High Speed[2]	Low/ Moderate Speed	High Speed	Low/ Moderate Speed	High Speed
Low	Low	E	E	D	C	C	B
	High[4]	E	D	D	C	B	A
High[3]	Low	D	D	C	B	B	A
	High[4]	C	C	C	A	A	A

A = highest friction demand, E = lowest friction demand

[1] Traffic Designations: Low ($ADT_{2\text{-way}} < 5{,}000$ veh/day) Moderate ($5{,}000 \le ADT_{2\text{-way}} \le 25{,}000$ veh/day)
High ($ADT_{2\text{-way}} > 25{,}000$ veh/day)

[2] Speed Designations: Low/Moderate (≤ 45 mi/hr [≤ 72 km/hr]) High (> 45 mi/hr [> 72 km/hr])

[3] Project contains multiple locations with considerably tight horizontal curves (with possibly inadequate super-elevation) and/or steep vertical grades.

[4] Project contains a considerable number of geometric design features that will increase the number of driving maneuvers and make the driving environment more difficult.

provides a means for selecting pairs of DFT(20) and MTD that will satisfy the following friction ranges:

Friction Design Category	*F(60) Range*
A	≥36.0
B	32.0 to 35.9
C	28.0 to 31.9
D	24.0 to 27.9
E	20.0 to 23.9

For instance, if F(60) must be at least 32 (friction design category B) and the long-term value of DFT(20) is estimated to be 60, then a texture with a long-term MTD of 0.026 in. (0.65 mm) would be needed. Or, if F(60) must be at least 24 (category D) and the DFT(20) is 50, then MTD of 0.02 in. (0.52 mm) would be needed.

Table 6-2 provides typical ranges of MTD for newly constructed textures based on values reported in the literature and on field measurements made in this study. Also listed in this table are corresponding ranges of MTD that reflect the typical levels of wear experienced by each texture. These values can be used with information on friction requirements and long-term micro-texture (DFT(20)) to identify feasible textures for a project.

The friction–texture plots shown in Figure 6-3 and the macro-texture information provided in Table 6-2 have been used to identify feasible textures based on friction requirements. Table 6-3 identifies suitable general texture types for new concrete pavements with anticipated specific long-term DFT(20)

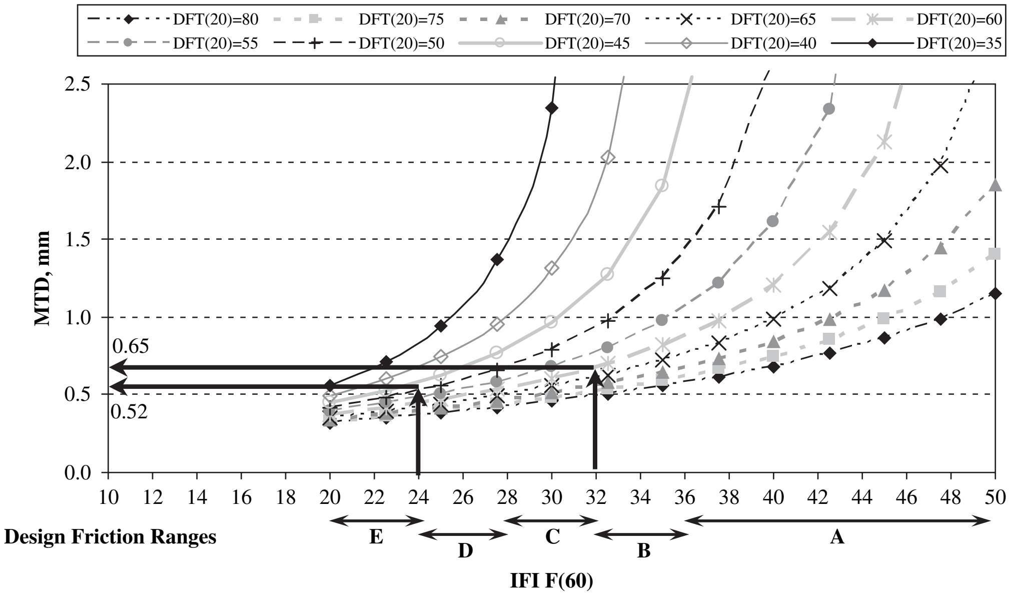


Figure 6-3. MTD versus F(60) and DFT(20).

Table 6-2. Typical ranges of macro-texture for new and aged surface textures.

Texture Type	Typical MTD for Newly Created Textures, mm	Typical MTD for Aged/Trafficked Textures, mm
New Pavement		
Burlap, Broom, and Standard Turf Drags	0.35 to 0.50	0.30 to 0.45
Heavy Turf Drag	0.50 to 0.90	0.40 to 0.80
Transverse and Transverse Skewed Tine	0.60 to 1.25	0.50 to 1.15
Longitudinal Tine	0.60 to 1.25	0.50 to 1.15
Longitudinal Diamond Grind	0.70 to 1.40	0.50 to 1.25
Longitudinal Grooving	0.80 to 1.50	0.70 to 1.40
EAC	0.90 to 1.60	0.75 to 1.50
Porous PCC	1.20 to 2.50	0.90 to 2.25
Restoration of Existing Pavement		
Longitudinal Diamond Grind	0.70 to 1.40	0.50 to 1.25
Longitudinal Grooving	0.80 to 1.50	0.70 to 1.40
Shotblasted PCC	1.00 to 1.50	0.80 to 1.40
HMA (dense-graded fine)	0.40 to 0.75	0.30 to 0.70
HMA (dense-graded coarse)	0.60 to 1.20	0.50 to 1.10
Ultra-thin Bonded Wearing Course	1.00 to 1.75	0.80 to 1.50

1 in. = 25.4 mm

Table 6-3. Identification of textures for new concrete pavements based on friction requirements and expected long-term micro-texture.

Friction Design Category	Long-Term DFT(20) Range	General Texture Type							
		Burlap, Broom, Std Turf Drag	Heavy Turf Drag	Tran Tine	Long Tine	Long Diamond Grind	Long Groove	EAC	Porous PCC
A (F(60)>36)	>80		✓	✓	✓	✓	✓	✓	✓
	70 to 80		✓	✓	✓	✓	✓	✓	✓
	60 to 70			✓	✓	✓	✓	✓	✓
	50 to 60						✓	✓	✓
	40 to 50								
	30 to 40								
B (F(60)>32)	>80		✓	✓	✓	✓	✓	✓	✓
	70 to 80		✓	✓	✓	✓	✓	✓	✓
	60 to 70		✓	✓	✓	✓	✓	✓	✓
	50 to 60			✓	✓	✓	✓	✓	✓
	40 to 50								✓
	30 to 40								
C (F(60)>28)	>80	✓	✓	✓	✓	✓	✓	✓	✓
	70 to 80		✓	✓	✓	✓	✓	✓	✓
	60 to 70		✓	✓	✓	✓	✓	✓	✓
	50 to 60		✓	✓	✓	✓	✓	✓	✓
	40 to 50			✓	✓	✓	✓	✓	✓
	30 to 40							✓	✓
D (F(60)>24)	>80	✓	✓	✓	✓	✓	✓	✓	✓
	70 to 80	✓	✓	✓	✓	✓	✓	✓	✓
	60 to 70	✓	✓	✓	✓	✓	✓	✓	✓
	50 to 60		✓	✓	✓	✓	✓	✓	✓
	40 to 50		✓	✓	✓	✓	✓	✓	✓
	30 to 40			✓	✓	✓	✓	✓	✓
E (F(60)>20)	>80	✓	✓	✓	✓	✓	✓	✓	✓
	70 to 80	✓	✓	✓	✓	✓	✓	✓	✓
	60 to 70	✓	✓	✓	✓	✓	✓	✓	✓
	50 to 60	✓	✓	✓	✓	✓	✓	✓	✓
	40 to 50		✓	✓	✓	✓	✓	✓	✓
	30 to 40		✓	✓	✓	✓	✓	✓	✓

values, and Table 6-4 indicates suitable options (including thin asphalt treatments) for re-texturing existing concrete pavements to enhance surface friction characteristics.

Tables 6-3 and 6-4 were developed for aged/trafficked surfaces, the upper end of the MTD ranges listed in Table 6-2, and the upper end of each DFT(20) range. Although this table illustrates texture possibilities, detailed analyses of friction must be performed to ensure that each viable texturing option meets the established friction requirement(s).

Concerning the identification of feasible texturing options for friction, the following items should be noted:

1. Polished DFT(20) values depend on the type and quality of the aggregate used in the surface mixture. Aggregates that exhibit the highest levels of polish resistance and resistance to wear typically are composed of hard, strongly bonded, interlocking mineral crystals embedded in a matrix of softer minerals (Folliard and Smith, 2003; Liang, 2003).
2. The relationship between BPN and DFT(20) is expressed by the following equation (Henry, 2000):

$$\text{BPN} = 57.9 \times \text{DFT}(20) + 23.1 \qquad \text{Eq. 6-1}$$

3. Consideration could be given to adjusting the minimum F(60) friction design values based on climatic conditions (e.g., values should be increased for locations with high wet-pavement times).
4. The IFI F(60) friction value is fairly closely aligned with FN40S values, particularly for lower texture depths. For the ranges of $F(60) < 50$ and $MTD \leq 0.04$ in. ($MTD \leq 1$ mm), there is less than 3% difference between F(60) and FN40S

Table 6-4. Identification of textures for restoration of existing concrete pavements based on friction requirements and expected long-term micro-texture.

Friction Design Category	Long-Term DFT(20) Range	General Texture Type					
		Long Diamond Grind	Long Groove	Shot-Abrade	Thin HMA Overlay (Fine Mix)	Thin HMA Overlay (Coarse Mix)	Ultra-Thin Bonded Wearing Course
A (F(60)>36)	>80	✓	✓	✓	✓	✓	✓
	70 to 80	✓	✓	✓	✓	✓	✓
	60 to 70	✓	✓	✓		✓	✓
	50 to 60		✓	✓			✓
	40 to 50						
	30 to 40						
B (F(60)>32)	>80	✓	✓	✓	✓	✓	✓
	70 to 80	✓	✓	✓	✓	✓	✓
	60 to 70	✓	✓	✓	✓	✓	✓
	50 to 60	✓	✓	✓		✓	✓
	40 to 50						✓
	30 to 40						
C (F(60)>28)	>80	✓	✓	✓	✓	✓	✓
	70 to 80	✓	✓	✓	✓	✓	✓
	60 to 70	✓	✓	✓	✓	✓	✓
	50 to 60	✓	✓	✓	✓	✓	✓
	40 to 50	✓	✓	✓		✓	✓
	30 to 40						✓
D (F(60)>24)	>80	✓	✓	✓	✓	✓	✓
	70 to 80	✓	✓	✓	✓	✓	✓
	60 to 70	✓	✓	✓	✓	✓	✓
	50 to 60	✓	✓	✓	✓	✓	✓
	40 to 50	✓	✓	✓	✓	✓	✓
	30 to 40	✓	✓	✓		✓	✓
E (F(60)>20)	>80	✓	✓	✓	✓	✓	✓
	70 to 80	✓	✓	✓	✓	✓	✓
	60 to 70	✓	✓	✓	✓	✓	✓
	50 to 60	✓	✓	✓	✓	✓	✓
	40 to 50	✓	✓	✓	✓	✓	✓
	30 to 40	✓	✓	✓	✓	✓	✓

and 3 to 5% difference for the range F(60) < 50 and 0.04 in. < MTD ≤ 0.08 in. (1 mm < MTD ≤ 2 mm). Thus, FN40S can provide a general indication of the F(60) design levels.

5. The textures identified in these tables are based solely on assumed long-term friction needs. Consideration of costs, constructability, and experience may dictate elimination of specific textures from consideration.

Step 3—Feasible Textures Based on Noise Requirements and Preferences

There is no nationally recognized requirement for the maximum level of noise (either at the source or at a point on the wayside) that can be generated by a highway pavement. However, Code of Federal Regulations (CFR) Title 23, Part 772, governs the amount of overall wayside noise that can be predicted to occur for projects to qualify for federal cost sharing. This CFR does not restrict the use of noise-reducing pavement (Bernhard and Wayson, 2005).

In this step, the qualitative noise level categories presented in Chapter 5 are considered. These categories can be fitted to various conditions/scenarios defined by traffic speed, volume, and composition; facility setting (urban versus rural); and adjacent land use. Metropolitan projects in noise-sensitive areas (e.g., residences, parks, and hospitals) and having higher traffic speeds and volumes (trucks and overall) will require lower levels of exterior noise, thereby narrowing the number of texturing options. Projects in rural settings, on the other hand, will not be as demanding of limits on exterior noise, thereby resulting in more texturing options.

Table 6-5 lists target initial exterior noise levels for untrafficked highway projects, based on the forecast traffic characteristics and the noise-sensitivity of the adjacent environment. Only qualitative noise levels A, B, and C are included in this table because all textures can be designed and constructed to meet at least level C requirements. Low-speed facilities (<35 mi/hr [<56 km/hr]) are not included in Table 6-5 because pavement–tire noise at low speeds is secondary to propulsion/engine noise; texture selection in these instances will be more rudimentary. The noise levels given in the table are representative of those generated at the source by a vehicle traveling at 60 mi/hr (96 km/hr); noise characteristics at other speeds (e.g., the moderate category) are proportional to those for 60 mi/hr (96 km/hr).

Unless otherwise desired, feasible textures can be identified on the basis of exterior, at-the-source noise target levels. The data collected in this study show a general relationship between the noise measured at the source and the noise measured inside the vehicle. If lower interior noise levels are required for a project, then a lower target level should be selected as the basis for the identification of feasible textures.

Once a target noise level has been established to meet the exterior noise requirements and/or interior vehicle noise preferences of the project, the noise–texture alternatives in Tables 6-6 and 6-7 can be used to identify candidate textures for new construction/reconstruction and restoration projects, respectively, on the basis of noise.

The selection involves determining the general textures suitable for the desired target noise level (A, B, or C). These are designated by checkmarks (√) under the appropriate target noise level column (or multiple columns for some textures). More specific applications of each general texture can then be evaluated, based on the favorable noise characteristic provided by the particular features of the texture, as illustrated by arrows that stretch across a particular target level or multiple target levels. Textures spanning target levels A and/or B are also candidates for target level C; however, higher costs or other factors may eventually preclude them from being feasible options.

Identifying specific textures that satisfy both the friction and noise target levels requires iteration of Steps 2 and 3 because texture features (i.e., the texture produced by drag devices) and dimensions (i.e., groove spacings, depths, and widths)

Table 6-5. Target levels for exterior noise.

Noise-Sensitivity of Adjacent Land Use	Traffic Speed	Low Traffic[1]		Moderate Traffic[1]		High Traffic[1]	
		Low % Trucks[2]	High % Trucks[2]	Low % Trucks	High % Trucks	Low % Trucks	High % Trucks
Low[3]	Moderate[4]	C	C	C	C	C	B
	High[4]	C	C	C	B	B	B
High[3]	Moderate	C	C	B	A	B	A
	High	C	B	A	A	A	A

A = low noise, B = fairly low noise, C = moderate noise.

[1] Traffic Designations: Low (ADT$_{2\text{-way}}$ < 5,000 veh/day). Moderate (5,000 ≤ ADT$_{2\text{-way}}$ ≤ 25,000 veh/day) High (ADT$_{2\text{-way}}$ > 25,000 veh/day)

[2] Truck Volume Designations: Low (≤ 15 percent). High (> 15 percent)

[3] Adjacent Land Use: Low (rural undeveloped or urban developed with non-critical zoning designations [e.g., industrial, commercial]), High (urban partly or fully developed with critical zoning designations [e.g., residential, parks, schools, hospitals])

[4] Traffic Speed Designations: Moderate (35 to 45 mi/hr [56 to 72 km/hr]) High (>45 mi/hr [>72 km/hr])

Table 6-6. Identification of textures for new concrete pavements based on noise requirements (and/or preferences).

General Texture	Specific Texture Features/Dimensions	Candidate Textures by Target Noise Level			Remarks
		A	B	C	
Long Drag			✓	✓	
	Burlap		↔	↔	Greater texture depth provided by heavy turf drag will generate more noise, but will also yield higher friction.
	Broom or standard turf		↔	↔	
	Heavy turf		↔	↔	
Tran Tine (Uniform Spacing)				✓	Uniform spacing highly prone to creating objectionable tonal spikes. Use on high-speed facilities should be carefully considered.
	Narrow spacing (≤ 0.75 in. avg.)		↔	↔	Wider average spacing prone to generating greater overall noise.
	Wider spacing (>0.75 in. avg.)			↔	
	Shallow grooves (<3.2 mm)		↔	↔	Deeper grooves will generate more noise than shallower grooves, in part because deeper grooves are normally wider and because more mortar is displaced creating additional positive texture (ACPA, 2006).
	Standard grooves (3.2 mm)			↔	
	Deep grooves (> 3.2 mm)			↔	
Tran Tine (Variable Spacing)			✓	✓	Variable spacing can significantly reduce or remove tonal spikes, but overall noise likely to be same or greater, partly due to increased tine spacing used to create variable pattern (ACPA, 2006).
	Narrow spacing (≤ 1.25 in. avg.)		↔	↔	Wider effective average spacing prone to generating greater overall noise.
	Wider spacing (>1.25 in. avg.)			↔	
	Shallow grooves (<3.2 mm)		↔	↔	See above comment.
	Standard grooves (3.2 mm)		↔	↔	
	Deep grooves (> 3.2 mm)			↔	
Tran Skewed Tine (Variable Spacing)			✓	✓	Combination of skewed and variable grooves can effectively eliminate tonal issues and have been shown to reduce overall noise.
	Narrow spacing (≤ 1.25 in. avg.)		↔	↔	Wider effective average spacing prone to generating greater overall noise.
	Wider spacing (>1.25 in. avg.)		↔	↔	
	Shallow grooves (<3.2 mm)		↔	↔	See above comment.
	Standard grooves (3.2 mm)		↔	↔	
	Deep grooves (> 3.2 mm)			↔	
Long Tine			✓	✓	
	Straight grooves		↔	↔	At the sacrifice of some friction, straight grooves generate a little less noise than meandering grooves. Constructability of longitudinal meander tine is low.
	Meandering grooves		↔	↔	
	Narrow spacing (≤ 0.75 in. avg.)		↔		Preliminary indications suggest that noise may be reduced using narrower tine spacings.
	Wider spacing (>0.75 in. avg.)		↔	↔	
	Shallow grooves (<3.2 mm)	↔	↔		Deeper grooves will generate more noise than shallower grooves, in part because deeper grooves are normally wider and because more mortar is displaced creating additional positive texture (ACPA, 2006)
	Standard grooves (3.2 mm)		↔	↔	
	Deep grooves (> 3.2 mm)		↔	↔	
Long Diamond-Grind		✓	✓	✓	
	Narrow spacers (≤ 0.11 in. avg.)	↔	↔		Conventional wisdom holds that narrower spacings produce less noise than wider spacings. However, data from this study show conflicting results. Research by others suggests that the profile of the fins produced by the grinding operation are more of a factor (ACPA, 2006).
	Wider spaces (>0.11 in.)	↔	↔		
	Shallow grooves	↔	↔		For a fixed spacing, shallower grooves will yield lower texture depths, which generate less noise.
	Deep grooves	↔	↔		
Long Groove		✓	✓	✓	
	Narrow spacing (≤ 0.50 in.)	↔	↔		Increased groove spacing results in lower overall noise.
	Wider spacing (0.75 in. std.)	↔	↔		
	Shallow grooves	↔	↔		Increased groove depth results in greater overall noise.
	Deep grooves	↔	↔		
EAC & Porous PCC		✓	✓	✓	Research from other countries indicates low levels of noise can be successfully achieved with these textures. However, experience with their use in the U.S. is very limited (only one EAC site was tested in this study). Careful consideration should be given before accepting either as a feasible option.
	Shallow texture	↔	↔		Increased depth results in greater overall noise.
	Deep texture	↔	↔		

Table 6-7. Identification of textures for friction restoration of existing concrete pavements based on noise requirements (and/or preferences).

General Texture	Specific Texture Features/Dimensions	Candidate Textures by Target Noise Level			Remarks
		A	B	C	
Long Diamond-Grind		✓	✓	✓	
	Narrow spacing (≤ 0.11 in. spacers) Wider spacing (>0.11 in. spacers)	↔ ↔	↔ ↔		Conventional wisdom holds that narrower spacings produce less noise than wider spacings. However, data from this study show conflicting results. Research by others suggests that the profile of the fins produced by the grinding operation are more of a factor (ACPA, 2006).
	Shallow grooves Deep grooves	↔ ↔	↔ ↔		For a fixed spacing, shallower grooves will yield lower texture depths, which generate less noise.
Long Groove		✓	✓	✓	
	Narrow spacing (≤ 0.50 in.) Standard spacing (0.75 in.)	↔ ↔	↔ ↔		Increased groove spacing results in lower overall noise.
	Shallow grooves Deep grooves	↔ ↔	↔ ↔		Increased depth results in greater overall noise.
Shot-Abrade		✓	✓	✓	
	Shallow texture Deep texture	↔ ↔	↔ ↔		Increased depth results in greater overall noise.
Thin HMA Overlay		✓	✓	✓	
	Fine Dense-Graded Mix Coarse Dense-Graded Mix	↔ ↔	↔ ↔		Fine mixes have more sand-sized particles which results in decreased texture depths and, subsequently, lower overall noise.
Ultra-Thin Bonded Wearing Course		✓	✓	✓	
	Fine Mix (0.1875-in.) Coarse Mix (0.375-in.)	↔ ↔	↔ ↔		Fine mixes, characterized by a smaller top-size aggregate, will have decreased texture depths and, subsequently, lower overall noise.

largely determine the texture depth (MTD or MPD), which directly influences the amount of friction and noise that can be expected.

Chapter 2 presented examples of texture depth associated with different tine dimensions. This information can serve as a starting point in estimating texture depth, which can then be used to evaluate friction (along with the properties of the expected aggregate) and noise.

Step 4—Selection of the Preferred Texturing Alternative

The last step in the texture selection process involves evaluating the adequacy of feasible textures with consideration of other important surface characteristics, such as splash/spray, fuel consumption and rolling resistance, and cost-effectiveness.

Consideration of Other Surface Characteristics

Because of the implications to highway safety through better visibility, consideration must be given to the splash/spray and other surface characteristics.

- Splash/spray—Increased macro-texture facilitates surface drainage and results in decreased splash/spray intensity and duration, thus improving visibility (Pilkington, 1990).
  - A porous structure (e.g., porous PCC) through which water can be drained vertically and then run off laterally through the road, rather than on its surface, is the optimum surface for splash/spray.
  - Splash/spray is less significant on transverse-tined pavements than on longitudinal-tined pavements (Kuemmel, et al., 2000), due to the better surface drainage provided by the lateral channels.
  - Less splash/spray is developed on transverse-tined pavements than on dense-graded asphalt (FHWA, 1996b).
- Driver perceptions of handling.
  - Longitudinal-tine spacings greater than 0.75 in. (19 mm) are particularly objectionable to drivers of small vehicles (FHWA, 1996b).
  - Motorcycle drivers report a perception of instability on longitudinally grooved roads (FHWA, 1980).
  - Narrower grooves (e.g., 0.1 in. versus 0.125 in. [2.5 versus 3.2 mm]) reduce the vehicle tracking influence (ACPA, 2006).
- Rolling resistance/fuel consumption—Roads with high levels of micro-texture and macro-texture result in increased rolling resistance and, subsequently, increased fuel consumption.
- Tire wear—Both micro-texture and macro-texture contribute to tire wear, with micro-texture contributing more significantly to such wear.

- Light reflection/retro-reflection and glare—High levels of macro-texture help break up possible water levels in the wheel tracks (Sandberg, 1998).

Economics

The final assessment of feasible textures involves costs—both the initial cost of constructing the texture and its long-term or life-cycle cost. Rough estimates of the unit costs associated with constructing the various texturing options on new concrete pavements and re-texturing options for existing pavements are provided in Chapter 2. Examination of the costs associated with new textures indicates a substantial difference in cost between traditional formed textures (drags and/or tines) and the more labor- and technology-intensive cut textures (ground or grooved), exposed aggregate textures, and porous concrete. For re-texturing, there appears to be a basic cost advantage to shot-abrading over grinding, grooving, and thin resurfacing with asphalt mixes. However, depending on the depth of diamond grinding and the hardness of the aggregate (which affects spacing), grinding costs could be equal to or less than alternatives.

The initial costs provided in Chapter 2 can be used as part of a pavement evaluation strategy that considers the design life and projected maintenance and rehabilitation activities. Life-cycle cost analysis (LCCA) techniques, such as net present value (NPV) and equivalent uniform annual cost (EUAC), may be used to identify the texture(s) with the lowest life-cycle costs.

Example Application of Texture Selection Process

This section provides an example to illustrate the application of the texture selection process. The example given is for a project involving the reconstruction (using PCC) of a four-lane freeway with the following features:

- The project is located in a suburb of a large city in a wet non-freeze climate (annual precipitation >55 in. [1,400 mm]).
- The land adjacent to the highway facility is mostly a mix of professional buildings and residential subdivisions.
- The current two-way ADT is approximately 35,000 veh/day and, although there are occasions of congested traffic flow, most of the time, traffic is in free flow condition at the posted speed limit of 55 mi/hr (89 km/hr).
- The percentage of heavy commercial trucks that use the facility is estimated to be 12 percent.
- The freeway has partially controlled access, with interchanges every 1 to 1.5 miles (1.6 to 2.4 km).
- The terrain is mildly flat; there are no major horizontal curves.
- The fine aggregate to be used in the concrete mix is a blend of natural and manufactured sand, and the coarse aggregate is crushed limestone. Historical data on the polishing characteristics of the blended fine aggregate indicate a long-term DFT(20) of 60 is expected.
- Grinding or grooving of the pavement post-construction is not permitted; there is no local experience with porous concrete and EAC.
- Tire whine complaints were reported in the recent past and should be avoided.

Steps 1 and 2: The information in Table 6-1 indicates that the project is best represented by friction design category B. The IFI F(60) minimum friction level for this category is 32, but because of the wet environment, a minimum friction of 36 would be desired. For this value and the long-term DFT(20) value of 60, and considering the exclusion of certain texturing methods, Table 6-3 indicates that transverse tining, transverse skewed tining, and longitudinal tining are the most feasible options.

Step 3: Because the project is in a noise-sensitive environment and considering the project's traffic characteristics, Table 6-5 indicates that the selected texture must reduce exterior noise to the 100 to 102 dB(A) range (qualitative noise level A). Table 6-6 shows that, of the three friction-based feasible textures, only longitudinal tining with certain features/dimensions will meet the criteria—specifically, narrowly spaced grooves of shallow or standard depth.

Based on information provided earlier in Table 2-2, 0.75-in. (19-mm) spaced longitudinal tines with shallow groove depths can be expected to provide an MTD value of about 0.03 in. (0.8 mm). For this value and the long-term DFT(20) value of 60, Figure 6-6 indicates that this texture just barely meets the minimum IFI F(60) = 36 criterion. A standard-depth longitudinal tine with slightly higher MTD value would better satisfy this criterion. Thus, both textures would be considered as the final feasible options and would be evaluated for other surface characteristics and economics in Step 4.

Texture Construction Specifications and Practices

Appendix F, available on line at the TRB website, contains sample guide specifications for the following selected group of concrete textures that provide good friction and noise characteristics on high-speed pavements:

- Heavy turf drag
- Transverse skewed variable tine
- Longitudinal tine
- Longitudinal diamond grind
- Longitudinal groove.

Successfully constructing these textures requires great attention to detail to both the materials production and construction processes. Good QC procedures combined with a statistically based QA program will help ensure that the as-built texture provides the friction and noise characteristics for which it was designed. Therefore, when specifying the depth of grooves and/or texture depth (as measured by the sand patch method, CT Meter, or other texture devices), it is important to account for the expected loss of macro-texture over time/traffic. Important considerations in constructing the selected textures successfully follow:

Mix Workability—For drag and tine textures, uniform concrete slump that is not too dry (workable mix) must be maintained throughout the paving process. Slight adjustments to the mix (within the limits of specified concrete mix), such as increasing the slump, adjusting the sand content, or adding a retarder, may be required to achieve the desired workability.

Texturing Operations—

- Drag and tine equipment (preferably a tine and cure machine) should allow the operator to maintain a consistent distance behind the paving and finishing operations, apply the proper amount of pressure (uniformly over the width of the paving) on the drag and/or tine assemblies, hinge the tine rake to optimize the angle of tine insertion, and have the capability to water-mist the surface.
- Drag and tine operators should be capable of monitoring texturing characteristics closely and making proper adjustments in response to site conditions (e.g., changes in mix consistency, rapid drying of the mix due to high winds and/or temperatures, delays in the paving and finishing operations, and buildup of mortar on the drag and/or tines). Timing of the texturing operation is critical: texturing too early may result in grooves filling up with mortar or surface tearing, and texturing too late may result in reduced groove depth (Iowa DOT, 2007).
- For heavy turf drags, the potential for significant mortar build-up and release should be considered because this can influence the surface profile and increase roughness.
- The speed of diamond grinding operations will be influenced by the hardness of the aggregate and the depth of cut. Grinding of pavements with extremely hard aggregate (e.g., quartzite) requires more time and effort than projects with softer aggregate, such as limestone (Correa and Wong, 2001).

Curing and Protection—For drag and tine textures, immediate application of curing compound or membrane following the texturing operation is essential to achieve good pavement surface durability. If the pavement cures too quickly, the mortar forming the texture ridges will not set properly, its durability will be reduced, and its friction (and noise) properties will be diminished more quickly (FAA, 2004). Generally, curing compounds can be applied earlier for longitudinal dragging and tining operations than for transverse tining operations.

Quality Control (QC)—Continuous evaluation and measurement of groove dimensions created by tining will help identify and correct deviations from the design profile. Random checks of depth may be made using a tire tread depth gauge or similar tool together with visual checks of the amount of mortar deposited on the surface by the tining operation and the straightness and width of the grooves; deeper tine penetrations generally result in more ragged and widened (at the top) grooves.

Quality Assurance (QA)—Groove and/or texture depth measurements on hardened concrete should be made to determine compliance with texture specifications. The measurements should be made at random locations throughout a paving run (or lot) at the earliest possible time following the texturing operation. The surface at the locations of testing should be wire brushed or lightly scraped with a steel straightedge to remove all mortar deposits that could affect the measurements.

Structural Design Considerations—Because diamond grinding generally reduces slab thickness by 0.19 to 0.25 in. (4 to 6 mm), it can influence the cracking potential of a concrete pavement. This is particularly true if the grinding is performed shortly after construction to serve as the initial surface texture. Research has indicated that a 0.25-in. (6-mm) reduction in slab thickness can result in roughly a 30% reduction in fatigue life (Rao et al., 1998). Thus, where diamond grinding is to be used as the initial texture, measures should be considered to offset this effect (e.g., increased thickness or strength requirements). Diamond grinding of an older pavement has less effect on fatigue life because of the strength gain with time (typically 20% higher than the design strength).

CHAPTER 7

Conclusions and Recommendations for Future Research

Conclusions

Major conclusions of the study consist of the following:

- PCC surface textures with the overall lowest noise levels include the longitudinal diamond-ground and longitudinal grooved textures, followed by longitudinal-tine and longitudinal-drag textures. High levels of friction can be achieved with ground, grooved, and tined textures, particularly if good-quality aggregate is used in the concrete mixture. Friction for longitudinal-drag textures can become inadequate if a deep texture ($MTD > 0.8$ mm [0.03 in.]) is not achieved at time of construction and/or polish-susceptible aggregate is used.
- Although uniformly spaced transverse-tine textures can produce moderate levels of overall noise, they are highly prone to creating objectionable tones. Closer spacing (0.5 in. [12.7 mm] or less) and shallower grooves can help reduce pavement–tire whine and overall noise. Variably spaced transverse-tine and skewed transverse-tine textures can result in moderately low levels of overall noise and can significantly reduce or eliminate objectionable tonal spikes. High levels of friction can be achieved with all three of these textures, particularly if good-quality aggregate is used.
- Although the EAC and shotblast textures evaluated in this study showed relatively high overall noise and low-to-moderate friction, the number of sections included in the evaluation (1 of each) was insufficient for a proper determination of noise and friction characteristics. Additional research is needed to verify indications from other countries that low levels of noise and adequate levels of friction can be successfully achieved with these textures.
- Asphalt surfacings tested in this study (thin HMA overlay and proprietary ultra-thin bonded wearing course) exhibited low to moderately low overall noise and moderately high levels of friction. Depending on the surfacing type and the hardness of the aggregate in the existing concrete surface, re-texturing via longitudinal diamond grinding or grooving can be more cost-effective than application of an asphalt surfacing.
- Based on extensive friction/micro-texture testing and available concrete mixture information, the use of higher quality aggregates in the concrete mixture helps maintain the micro-texture qualities needed for friction.
- Loss of concrete pavement macro-texture over time/traffic is greatest for diamond-ground textures (0.015 to 0.02 in. [0.4 to 0.5 mm]) and lowest for longitudinally grooved and dragged textures (0.002 to 0.003 in. [0.05 to 0.08 mm]). The geometric shape (i.e., narrow fins) of the diamond-ground texture results in more substantial loss than textures with no grooves (drag textures) or those that have well-defined, widely spaced, and structurally sound grooves (longitudinal-groove textures).
- Considerable differences exist between texture depth measurements obtained using the CT Meter and the high-speed profiler. Although the difference in sampling rates of the two devices is probably a factor, the texture type and direction are more profound factors, with longitudinal textures creating greater measurement difficulties for the high-speed profiler.
- PSD analysis of pavement surface texture indicated that near-field SI noise is generally related to the PSD texture parameters L_4/L_{63}, A_1/A_2, and PW.
- Detailed efforts to model SI as a function of various texture parameters (not just PSD texture parameters) were somewhat successful; the best predictive model ($R^2 = 0.77$) yielded SI as a function of A_1/A_2, RMS, and texture direction. Correlation analyses further indicated that reducing higher wavelength texture and increasing lower wavelength texture (i.e., decreasing the L_4/L_{63} or A_1/A_2 ratios, and reducing PW) results in reduced noise.
- ANOVA and regression analysis of texture (excluding PSD texture parameters), friction, and noise measurement data collected on all test sections, combined with other perti-

nent available test section data (e.g., age/traffic data, climate data, and pavement data), indicated that near-field SI noise is influenced to a large extent by texture depth and by texture type and direction. Also, SI is increased as the number of traffic applications is increased and the number/frequency of joints is increased.

Recommendations for Future Research

The following are recommendations for future research:

- Perform additional field testing on the existing test sections and the newly constructed test sections included in this study to allow for an evaluation of the long-term friction, noise, and durability characteristics of different texture forms.
- Conduct a study of the effects of aggregate used in the concrete surface layer on texture durability.
- Continue to evaluate and model texture–noise relationships for various surface textures, with special consideration of PSD texture parameters.
- Conduct investigations to enhance the methods for field-measuring friction and noise characteristics of pavement surfaces.
- Conduct investigations of EAC and other textures to develop a better understanding of the friction, noise, and durability characteristics of these and others.

References

Abe, H., Henry, J.J., Wambold, J., and Tamai, A. (2000) "Measurement of Pavement Macrotexture with Circular Texture Meter," *Transportation Research Record 1764,* Transportation Research Board, National Research Council, Washington, DC.

AASHTO TP076-08. (2008) *Provisional Standard Test Method for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method,* AASHTO, Washington, DC.

AASHTO. (2008) *Guide for Pavement Friction,* AASHTO, Washington, DC.

ACI. (1988) *Texturing Concrete Pavement,* ACI Committee 325, ACI-325.6R-88, ACI, Detroit, MI.

ACPA. (2000) "Concrete Pavement Surface Textures," *Concrete Pavement Technology and Research Special Report SR902P,* ACPA, Skokie, IL.

ACPA. (2006) "Rules of Thumb on Pavement Noise," *R&T Update,* ACPA, Skokie, IL.

ASTM E 274. (1997) *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire,* ASTM, West Conshokocken, PA.

ASTM E 303. (2003) *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester,* ASTM, West Conshokocken, PA.

ASTM E 501. (2000) *Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests,* ASTM, West Conshokocken, PA.

ASTM E 524. (2000) *Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests,* ASTM, West Conshokocken, PA.

ASTM E 965. (2001) *Standard Test Method for Measuring Pavement Macro-texture Depth Using a Volumetric Technique,* ASTM, West Conshokocken, PA.

ASTM E 1136. (1989) *Standard Specification for a Radial Standard Reference Test Tire,* ASTM, Philadelphia, PA.

ASTM E 1845. (2001) *Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth,* ASTM, West Conshokocken, PA.

ASTM E 1911. (2002) *Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester,* ASTM, West Conshokocken, PA.

ASTM E 1960. (1998) *Standard Practice for Calculating International Friction Index of a Pavement Surface,* ASTM, West Conshokocken, PA.

ASTM E 2157. (2001) *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter,* ASTM, West Conshokocken, PA.

ASTM E 2380. (2005) *Standard Test Method for Measuring Pavement Texture Drainage Using an Outflow Meter,* ASTM, West Conshokocken, PA.

Applied Pavement Technology (APTech). (2001) "PCC Pavement Evaluation and Rehabilitation, Reference Manual," NHI Course 131062, NHI, Arlington, VA.

Ardani, A. and W. Outcalt. (2005) *PCCP Texturing Methods,* Report No. CDOT-DTD-R-2005-21, Colorado Department of Transportation, Denver, CO.

Beeldens, A., D. Van Gemert, and G. Caestecker. (2004) "Porous Concrete/Laboratory Versus Field Experience."

Bernhard, R.J. and R.L. Wayson. (2005) "An Introduction to Tire/Pavement Noise," *Report No. SQDH 2005-1,* The Institute for Safe, Quiet, and Durable Highways, Purdue University, West Lafayette, IN.

Billiard, G. (2004) Telephone interaction with Gary Billiard of Skidabrader.

Brennan, J.J. and G.M. Schieber. (2006). "US-69 Surface Texture and Noise Study," *Report No. KS-05-3,* Kansas Department of Transportation, Topeka, KS.

Chalupnik, J. (1996) "Predicting Roadside Noise Levels from Near Field Trailer Measurements," *NoiseCon 96 Proceedings,* Seattle, WA.

Chandler J., et al. (2003) "Quieter Concrete Roads: Construction, Texture, Skid Resistance, and Noise," *Transportation Research Laboratory Report TRL 576,* Crowthorne, Berkshire, UK.

Correa, A.L. and B. Wong. (2001) *Concrete Pavement Rehabilitation–Guide for Diamond Grinding,* FHWA, Washington, DC.

Donavan, P.R. (2003) "Evaluation of the Noise Produced by Various Grooved and Ground Textures Applied to Existing Portland Cement Concrete Pavement Surfaces: Measurements on the State Route 58 Mojave Bypass, June 23."

Donavan, P.R. and D.M. Lodico. (2008). *NCHRP Report 630: Evaluating Tire-Pavement Noise at the Source,* Transportation Research Board, National Research Council, Washington, DC.

Exline, M. (2004) Telephone interaction with Marvin Exline of Koch Materials.

FAA. (2004) "Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces," *Advisory Circular 150/5320-12-C, Change 2,* FAA, Washington DC.

FHWA. (1973) *Noise Standards and Procedures,* Policy and Procedure Memorandum 90-2, FHWA, Washington, DC.

FHWA. (1980) "Pavement Macro-texture Review," *Report No. FHWA/RD-80/505,* FHWA, Washington, DC.

FHWA. (1996a) "Surface Finishing of Portland Cement Concrete Pavements—Tire Pavement Noise and Safety Performance," *Report No. FHWA-SA-96-068,* FHWA, Washington DC.

FHWA. (1996b) "PCC Surface Texture Technical Working Group Findings," FHWA, Washington, DC.

FHWA. (2005) "Surface Texture for Asphalt and Concrete Pavements," *Technical Advisory T 5040.36,* FHWA, Washington, DC.

FHWA. (2006) "Highway Traffic Noise in the United States: Problem and Response." FHWA, Washington, DC.

FHWA. (2008) ROSAN$_V$ Technical Notes, FHWA Turner-Fairbanks Highway Research Center (TFHRC) website (www.tfhrc.gov/hnr20/rosan/rosandoc.htm)

Flintsch, G.W., et al. (2003) "Pavement Surface Macro-texture Measurement and Application," Transportation Research Board, Washington, DC.

Folliard, K.J. and K.D. Smith. (2003) *NCHRP Research Results Digest 281: Aggregate Tests for Portland Cement Concrete Pavements: Review and Recommendations,* Transportation Research Board, National Research Council, Washington, DC.

Hanson, D. (2002) "Tire/Pavement Noise Study for Michigan Department of Transportation," National Center for Asphalt Technology (NCAT), Auburn, AL.

Hanson, D. and R. James. (2004) "Colorado DOT Tire/Pavement Noise Study," *Report Number CDOT-DTD-R-2004-5,* Colorado Department of Transportation, Denver, CO.

Henry, J.J. (2000), *NCHRP Synthesis 291: Evaluation of Pavement Friction Characteristics,* Transportation Research Board, National Research Council, Washington, DC.

Hibbs, B.O. and R.M. Larson. (1996) "Tire Pavement Noise and Safety Performance—PCC Surface Texture Technical Working Group," *Report No. FHWA-SA-96-068,* FHWA, Washington, DC.

Hoerner, T.E., et al. (2003) "Current Practice of PCC Pavement Texturing," Paper presented at the 2003 Annual Meeting of the Transportation Research Board, Washington, DC.

ISO. (2002). *Characterization of Pavement Texture by Use of Surface Profiles, Part 2—Terminology and Basic Requirements Related to Pavement Texture Profile Analysis,* ISO, Geneva, Switzerland.

Iowa DOT. (2007) *Construction Manual,* Chapter 9 PCC Pavement, Iowa DOT, Ames, IA.

Kuemmel, D.A., et al. (2000) "Noise and Texture on PCC Pavements: Results of a Multi-State Study," *Report No. WI/SPR-08-99,* Wisconsin Department of Transportation, Madison, WI.

Liang, R.Y. (2003). "Blending Proportions of High Skid and Low Skid Aggregate," Final Report prepared for Ohio Department of Transportation, Columbus, OH.

Marks, V.J. (1996). "Variations of Tine Texturing of PCC Pavement," Final Report prepared for Research Project MLR-93-4, Iowa Department of Transportation, Ames, IA.

Marquart, M. (2003). "Tining Versus Carpet Dragging for Texturing PCC Pavements: Third Evaluation," Experimental Study ND 99-02, North Dakota Department of Transportation, Bismark, ND.

NCHRP. (2009) *NCHRP Research Results Digest 321: Guide for Pavement Friction—Background and Research,* Transportation Research Board, National Research Council, Washington, DC.

Neal, B., et al. (1978) "Surface Textures for PCC Pavements," *Report No. FHWA-CA-TL-78-14,* California Department of Transportation, Sacramento, CA.

Neal, B.F. (1985) "An Evaluation of PCC Pavement Tine Texturing Patterns," FHWA/Ca-TL-85/05, FHWA/Caltrans.

PIARC. (1987). "Report of the Committee on Surface Characteristics," Proceedings of the 18th World Road Congress, Brussels, Belgium.

PIARC. (1995) "Inventory of Road Surface Characteristics Measuring Equipment," ISBN 2 84060-29-3, PIARC Technical Committee on Surface Characteristics, Paris, France.

Pilkington, G.G. II. (1990) "Splash and Spray," Surface Characteristics of Roadways: International Research and Technologies, ASTM STP1031, ASTM, Philadelphia, PA.

Pottinger, M., and T. Yager. (1986) *The Tire Pavement Interface,* ASTM Special Technical Publication STP 929, ASTM, PA. Specifically the paper by Wambold, J., J.J. Henry, and R.R. Hegmon. 1986. "Skid Resistance of Wet-Weather Accident Sites,"

Rao, S.P., H.T. Yu, and M.I. Darter. (1998) "The Longevity and Performance of Diamond-Ground Pavements," Final Report prepared for ACPA, Skokie, IL.

Rasmussen, R., et al. (2007a). "The Little Book of Quieter Pavements," FHWA, Washington, DC.

Rasmussen, R., et al. (2007b). "Concrete Pavement Joint and Texture Effects on Tire-Pavement Noise," PowerPoint Presentation, National Concrete Pavement Technology Center and FHWA.

Sandberg, U. (1998) "Influence of Road Surface Texture on Traffic Characteristics Related to Environment, Economy, and Safety: A State-of-Art-Study Regarding Measures and Measuring Methods," VTI notat 53A-1997, Swedish National Road Association, Linkoping, Sweden.

Sandberg, U. and J.A. Ejsmont. (2002) *Tyre/Road Noise Reference Book,* ISBN 91-631-2610-9, Informex, Kisa, Sweden.

Scofield, L. (2003) "SR202 PCCP Whisper Grinding Test Sections—Construction Report," Final Report, ACPA.

SAE J1477. (2000) *Measurement of Interior Sound Levels of Light Vehicles,* SAE International, Warrendale, PA.

U.S. Federal Government. (2008) *Code of Federal Regulations (CFR) Title 23–Highways, Part 772–Procedures for Abatement of Highway Traffic Noise and Construction Noise,* U.S. GPO, Washington, DC.

Wambold, J.C., J.J. Henry, and R.R. Hegmon. (1986) "Skid Resistance of Wet Weather Accident Sites," *The Tire Pavement Interface,* ASTM STP929, ASTM, Philadelphia, PA.

Wittwer, D. (2004) Email interaction with David Wittwer of United Paving Contractors.

Abbreviations and Acronyms

A_1	Texture content in the 20 to 610 mm wavelength range
A_2	Texture content in the 2 to 10 mm wavelength range
AADT	Annual Average Daily Traffic
APB	Acceleration Pass-By
ASTM	American Society for Testing and Materials
CB	Coast-By
CPB	Controlled Pass-By
CPX	Close Proximity
CT Meter	Circular Texture Meter
dB	Decibel (sound pressure level unit of measurement)
dB(A)	A-weighted Decibel (weighting of sound frequencies sensitive to human ear)
DF Tester	Dynamic Friction Tester
DFT	Friction parameter associated with DF Tester
DFT(20)	DFT measured at 20 km/hr
DG	Diamond Ground or Diamond Grinding
EAC	Exposed Aggregate Concrete
EMTD	Estimated Mean Texture Depth
FN	Friction Number (friction parameter associated with locked-wheel friction tester)
FN40R	FN measured at 40 mi/hr using ribbed test tire
FN40S	FN measured at 40 mi/hr using smooth test tire
F(60)	Friction parameter associated with International Friction Index (friction measured at 60 km/hr)
HMA	Hot-Mix Asphalt
IFI	International Friction Index (defined by F(60) and S_P)
IRI	International Roughness Index
ISO	International Standards Organization
L_{eq}	Equivalent sound level
L_{max}	Maximum sound level
L_4	Texture profile level of the 4-mm octave band
L_{10}	Sound level that is exceeded 10 percent of the time
L_{63}	Texture profile level of the 63-mm octave band
MPD	Mean Profile Depth

MTD	Mean Texture Depth
NMAS	Nominal Maximum Aggregate Size
OBSI	On-Board Sound Intensity
OF Meter	Outflow Meter
OFT	Outflow Time
PCC	Portland Cement Concrete
$PI_{0.0}$	Profile Index using zero blanking band
PSD	Power Spectral Density
RMS	Root-Mean Square
SAE	Society of Automotive Engineers
SI	Sound Intensity
S_P	Speed number associated with International Friction Index
SPB	Statistical Pass-By
SPL	Sound Pressure Level
SPM	Sand Patch Method
SRTT	(ASTM) Standard Reference Test Tire
TCB	Trailer Coast-By
TO	Texture Orientation
TR	Texture Ratio
WP	Wheelpath

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation