Research Report – UCD-ITS-RR-13-54

Investigation of Tire Pavement Noise for Concrete Pavement Surfaces: Summary of Four Years of Measurements

June 2013

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June 2013
Research Report: UCPRC-RR-2013-12

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Version 1

Work Conducted as Part of Partnered Pavement Research Center Strategic Plan Element No. 4.39:
Field and HVS Evaluation of Noise Benefits of Open-Graded and Other Quieter Surfaces

PREPARED FOR:

California Department of Transportation
(Caltrans)
Division of Research, Innovation and System
Information

PREPARED BY:

University of California
Pavement Research Center
Davis and Berkeley

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DOCUMENT RETRIEVAL PAGE			UCPRC RESEARCH REPORT NO.: UCPRC-RR-2013-12
Title: Investigation of Tire/Pavement Noise for Concrete Pavement Surfaces: Summary of Four Years of Measurements			
Authors: A. Rezaei and J. Harvey			
Caltrans Technical Lead and Reviewer: L. Motumah			
Prepared for: California Department of Transportation, Division of Research, Innovation and System Information	**FHWA No.:** CA162375A	**Date Work Submitted:** September 29, 2014	**Date:** June 2013
Strategic Plan Element No.: 4.39	**Status:** Stage 6, final		**Version No.:** 1

Abstract:

The objectives of the four-year quieter concrete pavement research study presented in this report were to measure noise from tire/pavement interaction, pavement smoothness, and drainability characteristics of concrete pavement surface textures currently used on the California state highway network. This study also was undertaken to develop recommendations for safe, durable, and cost-effective concrete pavement surface textures that minimize noise from tire/pavement interaction.

The fourth and final year of this research study included testing on 60 test sections grouped by texture type as follows: 27 diamond ground (DG), 12 diamond grooved (Gr), 19 longitudinally tined (LT), 1 burlap drag (BD), and 1 longitudinally broomed (LB). Five of the 60 test sections were continuously reinforced concrete pavement (CRCP) and the rest were jointed plain concrete pavement (JPCP).

This report presents the results of measurements of tire/pavement interaction noise and of the pavement smoothness and surface drainability characteristics of concrete pavement textures commonly used for new construction finishes or pavement preservation and rehabilitation strategies. Tire/pavement interaction noise was measured using the on-board sound intensity (OBSI) method; smoothness was measured in terms of the International Roughness Index (IRI) using a wide-spot (RoLine^{TM}) laser; pavement surface drainability was measured using outflow meter measurements as well as in terms of Mean Profile Depth (MPD) and Mean Texture Depth (MTD).

The results indicate that the OBSI levels for the concrete pavement sections evaluated in this study ranged from 100 dBA to 112 dBA, which is the same as the range of OBSI levels for concrete pavement textures measured in other similar studies. The average OBSI levels for the three commonly used texture types in California (DG, Gr, and LT) where the textures were not worn out ranged from 104 to 107 dBA, with DG and Gr sections typically being quieter than LT sections of similar age and texture condition. For comparison, the OBSI levels for the experimental grind-and-groove sections averaged 101 dBA. The average IRI values for the DG, Gr, and LT sections across all three texture conditions (new, aged, or worn out) were 68, 81, and 96 inches/mile, respectively. The results for the outflow meter times and the MPD values indicate that diamond-grooved sections had a greater capacity for allowing water to move out from under the tire. This suggests that diamond-grooved concrete pavements would generally be more effective in reducing the risk of hydroplaning than diamond-ground or longitudinally tined concrete pavements.

Keywords: tire/pavement noise, smoothness, drainability, OBSI, IRI, MPD, concrete pavements, texture

Recommendations for Implementation:

This study makes the following recommendations for implementing quieter concrete pavement strategies in California:

1. Continue to use diamond grinding and diamond grooving to retexture existing concrete pavements to improve friction, hydroplaning and ride quality characteristics, and reduce traffic noise.
2. Develop specifications for producing longitudinal tining that limits positive texture on new concrete pavement texturing.
3. Develop specifications for measuring OBSI levels at the completion of new construction and pavement preservation/rehabilitation projects.
4. Continue development and implementation of the grind-and-groove texture for use especially in noise-sensitive areas.
5. Undertake a broader study to evaluate the effects of concrete pavement texturing procedures on smoothness for new construction and lane replacement projects to determine whether diamond grinding or grind-and-groove texturing might be worthwhile alternatives as a part of initial construction instead of longitudinal tining.

Related Documents:

- Ongel, A., J. T. Harvey, E. Kohler, Q. Lu, and B. D. Steven. (2008) Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results. (UCPRC-RR-2007-03)
- Ongel, A., J. T. Harvey, E. Kohler, Q. Lu, B. D. Steven, and C. L. Monismith. (2008) Summary Report: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results. (UCPRC-SR-2008-01)
- Kohler, E., and J. Harvey. (2011) Quieter Pavement Research: Concrete Pavement Tire Noise. (UCPRC-RR-2010-03)
- Kohler, E. (2011) Quiet Pavement Research: Bridge Deck Tire Noise Report (UCPRC-RR-2010-04)
- Rezaei, A., J. Harvey. (2012) Concrete Pavement Tire Noise: Third-Year Results (UCPRC-RR-2012-03)
- Guada, I.M., A. Rezaei, J.T. Harvey, and D. Spinner. (2014) Evaluation of Grind-and-Groove (Next Generation Concrete Surface) Pilot Projects in California. (UCPRC-RR-2013-01)
- Rezaei, A., J. Harvey. (2014) Investigation of Noise, Ride Quality and Macrotexture Trends for Asphalt Pavement Surfaces: Summary of Six Years of Measurements (UCPRC-RR-2013-11)

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DISCLAIMER STATEMENT

ACKNOWLEDGMENTS

The authors would like to thank Mark Hannum, who collected the field noise and IRI data, Irwin Guada who collected the surface texture and joint data, and Dr. Rongzong Wu, who assisted with management and analysis of the data. They would also like to thank the following people for technical direction and advice: Linus Motumah of Caltrans Pavement Program in the Division of Maintenance, who was the technical lead; T. Joe Holland of the Division of Research, Innovation and System Information, who was the PPRC project manager; and the members of the Caltrans Quieter Pavement Task Group.

PROJECT OBJECTIVES

The four-year quieter concrete pavement research study presented in this report was undertaken to determine tire/pavement interaction noise characteristics and other performance-related characteristics of concrete pavement surface textures currently used by the California Department of Transportation (Caltrans). This study had the following objectives:

- Determine the acoustic characteristics of noise generated by tire/pavement interaction on concrete pavement surface textures commonly used in California.
- Determine the smoothness and drainability characteristics of concrete pavement surface textures.
- Determine the effects of surface texture type and condition, pavement age since initial or last surface texturing, and pavement smoothness on tire/pavement interaction noise levels on concrete pavements.
- Determine the effects of surface texture type and condition on drainability capacity (i.e., effectiveness in reducing the risk of hydroplaning) of concrete pavements.
- Develop recommendations for safe, durable, and cost-effective concrete pavement surface textures that minimize tire/pavement interaction noise.

This report presents the results of measurements of noise from tire/pavement interaction and of the smoothness and drainability characteristics of concrete pavement surface textures commonly used in California. Tire/pavement interaction noise was measured using the on-board sound intensity (OBSI) method; smoothness was measured in terms of the International Roughness Index (IRI) using a wide-spot (RoLine™) laser; drainability was measured in terms of outflow meter flow, Mean Profile Depth, and Mean Texture Depth.

EXECUTIVE SUMMARY

In the early 2000s, the California Department of Transportation (Caltrans) identified a need for research into the acoustics, friction, durability, and related performance properties of pavement surfaces on the state highway network. Consequently, in November 2006, the Caltrans Pavement Program approved a research project to evaluate tire/pavement interaction noise characteristics and other pavement surface performance characteristics of existing and experimental asphalt pavements. In May 2008, the Pavement Program initiated a similar research study to focus on concrete pavements, and that study is the subject of this report.

This report presents the results of the fourth and final year of measurements of tire/pavement interaction noise, smoothness, and surface drainability characteristics for concrete pavement surface texture types commonly used in California: diamond ground (DG) and diamond grooved (Gr), which are used for pavement preservation and rehabilitation; and longitudinally tined (LT), which is used for new concrete pavements. The report also includes some results for concrete pavement sections with longitudinally broomed (LB) and burlap drag (BD) surface textures. The results of a related study that investigated tire/pavement noise and other surface texture characteristics for grinding projects on existing concrete pavement using the experimental grind-and-groove texture were presented in a separate 2014 report, "Evaluation of Grind-and-Groove (Next Generation Concrete Surface) Pilot Projects in California," UCPRC-RR-2013-01.

The objectives of the four-year quieter concrete pavement research study were:

- Determine the acoustic characteristics of noise generated by tire/pavement interaction on concrete pavement surface textures commonly used in California.
- Determine the smoothness and drainability characteristics of concrete pavement surface textures.
- Determine the effects of surface texture type and condition, pavement age since initial or last surface texturing, and pavement smoothness on tire/pavement interaction noise levels on concrete pavements.
- Determine the effects of surface texture type and condition on drainability capacity (i.e., effectiveness in reducing the risk of hydroplaning) of concrete pavements.
- Develop recommendations for safe, durable, and cost-effective concrete pavement surface textures that minimize tire/pavement interaction noise.

The first two years of the four-year study included some test sections that were in an advanced state of deterioration. These were dropped for the third and fourth years of measurements. In the fourth year of the study an imbalance in the number of commonly used textures was corrected in order to produce a factorial that was more representative of the texture types found on the state highway network. As a result, the fourth-year measurements included a total of 60 pavement sections, of which 23 were selected from previous years and

37 were new. The 60 test sections consisted of the following surface textures: 27 diamond ground (DG), 12 diamond grooved (Gr), 19 longitudinally tined (LT), 1 burlap drag (BG), and 1 longitudinally broomed (LB). Also, five of the 60 sections were continuously reinforced concrete pavements (CRCP), of which four were longitudinally tined (CRCP-LT) and one was diamond-ground (CRCP-DG). The remainder of the fourth-year sections and all of the sections in the previous three years of measurements were jointed plain concrete pavement (JPCP).

Most of the fourth-year test sections were evaluated within fifteen years after construction (LT, BD, and LB) or the last retexturing (DG and Gr). Information about the concrete mixes in each section was unavailable. Cement content, aggregate gradation, and other mix design variables may affect the initial texturing and how it changes over time, but these were not considered in this study because of the unavailability of the data.

As concrete pavement surface is degraded by years of traffic and by environmental effects, and the interaction of the two, the original texture eventually wears out and the surface can no longer be considered to represent that texture. This change is referred to as texture *aging*. To account for these changes, sections included in the original factorial for this study were classified as having *new, aged,* or *worn out* textures, with these categories based on actual texture condition and not the age of the texture. In the fourth year of the experiment, the worn out sections were removed in order to obtain concrete pavement sections that were representative of their initial texture type.

This report presents the results of measurements of noise from tire/pavement interaction and of the smoothness, and drainability characteristics of concrete pavement surface textures commonly used in California. Tire/pavement interaction noise was measured using the on-board sound intensity (OBSI) method. The noise measurements were analyzed to determine overall OBSI levels and OBSI levels for different frequencies at one-third octave bands. Pavement smoothness was measured in terms of the International Roughness Index (IRI) using a wide-spot (RoLine^{TM}) laser. Macrotexture properties were measured in terms of Mean Profile Depth (MPD) and Mean Texture Depth (MTD), which are very similar. The MPD values were measured using a laser texture scanner (LTS), while the MTD values were measured using the sand patch method. The outflow meter was used to measure drainability capacity, which is the ability of water to move out from under the tire through the texture thereby reducing the potential for hydroplaning. Joint dimensions were measured and three-dimensional scans of the pavement surface were used to calculate various texture parameters.

The results presented in this report focus primarily on the three concrete pavement textures commonly used in California—diamond ground (DG), diamond grooved (Gr) and longitudinally tined (LT)—and to a lesser extent on the other two concrete pavement textures considered in the study—burlap drag (BD) and longitudinally broomed (LB). Based on the results of the four-year study, the following conclusions can be drawn regarding tire/pavement interaction noise (OBSI), pavement smoothness (IRI), and the surface drainability characteristics of concrete pavement textures used on the California state highway network:

1. The OBSI levels on the concrete pavements evaluated in this study ranged from 100 dBA to 112 dBA across all five texture types. This is the same as the range of OBSI levels for concrete pavement textures measured in other similar studies.
2. The average overall OBSI levels for the diamond-ground (DG), diamond-grooved (Gr), and longitudinally tined (LT) sections where the textures were not worn out ranged from 104 to 107 dBA, with DG and Gr sections typically being quieter than LT sections. For comparison, the average OBSI level for the experimental grind-and-groove textured sections was 101 dBA (reported in a separate report).
3. The average frequency content of noise for the DG, Gr, and LT sections was similar, with maximum OBSI levels at 60 mph occurring between 800 and 1,000 Hz.
4. The relationship between OBSI versus age of the test sections since construction (LT) or the last retexturing (DG or Gr) showed wide scatter, indicating that age is not a good predictor of noise on concrete pavement because of environmental, traffic, and other pavement performance-related factors. However, the OBSI values for the 23 test sections with four years of measurements showed rates of increase in OBSI with age of 0.1, 0.3, and 0.8 dBA per year for the LT, Gr, and DG sections, respectively.
5. The average IRI values for the DG, Gr, and LT sections with new or aged texture conditions were 68, 81, and 96 inches/mile, respectively. Although there was no correlation between OBSI and IRI, test sections with higher IRI values typically had higher OBSI levels.
6. The outflow meter and the MPD measurements both indicate that Gr sections had a greater capacity for allowing water to move out from under the tire. This finding suggests that diamond-grooved concrete pavements would generally be more effective in reducing the risk of hydroplaning than diamond-ground or longitudinally tined concrete pavements.

This study makes the following recommendations for the development and implementation of quieter concrete pavement strategies in California:

1. Continue to use diamond grinding and diamond grooving to retexture existing concrete pavements to improve friction, hydroplaning, and ride quality characteristics, and to reduce traffic noise.

2. Develop specifications for producing longitudinal tining that limits positive texture on new concrete pavement texturing.
3. Develop specifications for measuring OBSI levels at the completion of new or pavement preservation/rehabilitation projects.
4. Continue development and implementation of the grind-and-groove texture for use especially in noise-sensitive areas.
5. Undertake a broader study to evaluate the effects of concrete pavement texturing procedures on smoothness for new construction and lane replacement projects to determine whether diamond grinding or grind-and-groove texturing might be worthwhile substitutes for longitudinal tining as part of initial construction.

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LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AADTT	Annual average daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
ACPA	American Concrete Pavement Association
ADF	Amplitude Distribution Function
ANOVA	Analysis of variance
BD	Burlap drag
CRCP	Continuously reinforced concrete
DG	Diamond ground
HVS	Heavy Vehicle Simulator
IRI	International Roughness Index
JPCP	Jointed plain concrete
LB	Longitudinally broomed
LT	Longitudinally tined
LTS	Laser texture scanner
MPD	Mean Profile Depth
MTD	Mean Texture Depth
NCHRP	National Cooperative Highway Research Program
NCPTC	National Concrete Pavement Technology Center
OBSI	On-board sound intensity
OFM	Outflow meter
PCC	Portland cement concrete
PPRC	Partnered Pavement Research Center
PST	Pavement Standards Team
QPR	Quieter Pavement Research
RMS	Root Mean Square
SRTT	Standard Reference Test Tire
TPTA	Tire Pavement Test Apparatus
UCPRC	University of California Pavement Research Center
VIF	Variance inflation factor

1 INTRODUCTION

In the early 2000s, the California Department of Transportation (Caltrans) identified a need for research into the acoustics, friction, durability, and related performance properties of pavement surface textures used on the state highway network. Consequently, in November 2006, the Caltrans Pavement Standards Team (PST) approved a research project to evaluate the tire/pavement noise characteristics and performance properties of existing asphalt pavements, including current Caltrans mixes and selected experimental mixes. In May 2008, the Caltrans Quieter Pavement Research Task Group initiated a similar research study to focus on rigid pavements, and that study is the subject of this report.

1.1 Project Goal and Objectives

The four-year quieter concrete pavement research study presented in this report was undertaken to determine tire/pavement interaction noise characteristics and other performance-related characteristics of concrete pavement surface textures currently used by Caltrans. This study had the following objectives:

- Determine the acoustic characteristics of noise generated by tire/pavement interaction on concrete pavement surface textures commonly used in California.
- Determine the smoothness and drainability characteristics of concrete pavement surface textures.
- Determine the effects of surface texture type and condition, pavement age since initial or last surface texturing, and pavement smoothness on tire/pavement interaction noise levels on concrete pavements.
- Determine the effects of surface texture type and condition on drainability capacity (i.e., effectiveness in reducing the risk of hydroplaning) of concrete pavements.
- Develop recommendations for safe, durable, and cost-effective concrete pavement surface textures that minimize tire/pavement interaction noise.

1.2 Overview of Study

This study involved the identification of concrete pavement test sections throughout the state and measuring tire/pavement interaction noise as well as other surface texture characteristics once each year over the duration of the study. The test section selection included the concrete pavement surface texture types commonly used in California: diamond ground (DG) and diamond grooved (Gr), which are used for pavement preservation and rehabilitation of existing pavements; and longitudinally tined (LT), which is used for new concrete pavements. This study also includes concrete pavement sections with longitudinally broomed (LB) and burlap drag (BD) textures, which are seldom used in California.

The field tests performed as a part of this study included measurements of tire/pavement interaction noise using the on-board sound intensity (OBSI) method; measurements of pavement ride quality (i.e., smoothness) in terms of the International Roughness Index (IRI) using a wide-spot (RoLine™) laser; and measurements of pavement surface drainability using outflow meter and Mean Profile Depth.

1.3 Scope of this Report

The first two years of the four-year study included some test sections that were in an advanced state of deterioration. These were dropped for the third and fourth years of measurements. In the fourth year of the study an imbalance in the number of commonly used textures was corrected in order to produce a factorial that was more representative of the texture types found on the state highway network. As a result, the fourth-year measurements included a total of 60 pavement sections, of which 23 were selected from previous years and 37 were new. The 60 test sections consisted of the following surface textures: 27 diamond ground (DG), 12 diamond grooved (Gr), 19 longitudinally tined (LT), 1 burlap drag (BG), and 1 longitudinally broomed (LB). Also, five of the 60 sections were continuously reinforced concrete pavements (CRCP), of which four were longitudinally tined (CRCP-LT) and one was diamond-ground (CRCP-DG). The remainder of the fourth-year sections and all of the sections in the previous three years of measurements were jointed plain concrete pavement (JPCP).

This report presents the results of the fourth and final year of measurements of noise from tire/pavement interaction, smoothness, and surface drainability characteristics for the five concrete pavement surface texture types evaluated. The results include analysis of the field measurements of noise and other performance characteristics of concrete pavement surface textures. Tire/pavement interaction noise measurements were analyzed to determine overall OBSI levels and OBSI levels for different frequencies at one-third octave bands. Pavement smoothness was measured in terms of the International Roughness Index (IRI) using a wide-spot (RoLine™) laser. Macrotexture properties were measured in terms of Mean Profile Depth (MPD) and Mean Texture Depth (MTD), which are very similar. The MPD values were measured using a laser texture scanner (LTS), while the MTD values were measured using the sand patch method. The outflow meter was used to measure drainability capacity, which is the ability of water to move out from under the tire through the texture thereby reducing the potential for hydroplaning. Joint dimensions were measured and three-dimensional scans of the pavement surface were used to calculate various texture parameters.

Overall, the results presented in this report focus primarily on the three concrete pavement textures commonly used in California—diamond ground (DG), diamond grooved (Gr) and longitudinally tined (LT)—and to a lesser extent on the other two concrete pavement textures considered in the study—burlap drag (BD) and longitudinally broomed (LB). The results provide useful conclusions regarding tire/pavement noise and other performance characteristics of concrete pavement surface textures from which recommendations were made for the development and implementation of quieter concrete pavement strategies in California.

2 TEXTURE TYPES AND TEST SECTION SELECTION

2.1 Description of Experiment Design, Texture Types and Texture Condition Categories

2.1.1 Overall Experiment Design

Table 2.1 shows the number of sections and the locations of pavement sites evaluated in each year of the study, grouped by texture type. Appendix A includes tables showing construction dates, last resurfacing dates, the dates of all OBSI and IRI measurements, ages at the time of measurement, and overall OBSI values for each of the four years of testing.

The experimental design for the first three years of measurement included up to three test sections at each test site. In Year 1 of the study, the set of test sections included 119 test sections at 47 sites, with 108 of the pavement sections located at 36 sites (i.e., three sections per site), two sections at one site, and nine sites with one section each. A number of sections were dropped from the experiment over the first three years of measurements due to construction that changed the surface texture or to other issues that changed the sections. In the fourth year, the study included a total of 60 pavement sections of which 23 sections were selected from previous years and 37 new sections were added. The new sections were added to focus on the three primary textures of interest, diamond ground, diamond grooved and longitudinally tined, and all of the burlap-drag and longitudinally broomed sections were dropped, except for the newer experimental test sections on State Route 58. The number of multi-section sites was also reduced in the fourth year to only those sites where the individual sections appeared to have differences in OBSI. Section QP-193 was subsequently dropped from the analysis because it showed signs of extreme raveling due to chain wear.

The fourth-year test sections were comprised of five texture types, with the following distribution of sections: 27 diamond ground (DG), 12 diamond grooved (Gr), 19 longitudinally tined (LT), one burlap drag (BD), and one longitudinally broomed (LB). Of these sections, 8 DG, 8 Gr, 6 LT, and the single BD and LB sections were measured for all four years, while the others were only measured in the fourth year. Among the sections in Year 4 was a new pavement type, *continuously reinforced concrete* (CRCP), which was introduced to the experimental design to enable study of the effect of this pavement type on the overall noise performance of concrete pavements. Four CRCP sections with longitudinally tined surface texture (CRCP-LT) and one with a diamond-ground surface texture (CRCP-DG) were measured for OBSI and IRI. The remainder of the fourth year sections and all of the sections in the previous three years of measurements were jointed plain concrete (JPCP) pavement.

Table 2.1: Summary of Texture Types and Sites Tested in Each Year

Texture Type	Number of Sections Used in Analyses	Sites
Burlap drag (BD)	Year 1: 37 Year 2: 31 Year 3: 31 Year 4: 1	QP-102, QP-104, QP-105, QP-106, QP-107, QP-113, QP-115, QP-116, QP-123, QP-126, QP-130, QP-137, QP-159 in Years 1 to 3, except by Years 2 and 3 the six sections at Sites QP-113 and QP-137 had been overlaid. Only QP-159 was kept in Year 4.
Diamond ground (DG)	Year 1: 32 Year 2: 24 Year 3: 23 Year 4: 27	QP-103, QP-114, QP-128, QP-129, QP-131, QP-132, QP-133, QP-134, QP-135, QP-147, QP-148, QP-155, QP-160, and QP-166 in Years 1 to 3, except: the nine sections at Sites QP-103, QP-114 and QP-135 were overlaid or had a lane shift by Year 2; Section QP-132.2 was not tested in Year 1 due to operator error but was tested in Years 2 and 3, data were not used in statistical analyses. QP-181, QP-182, QP-183, QP-184, QP-185, QP-186, QP-188, QP-193, QP-194, QP-195, QP-196, QP-197, QP-198, QP-200, QP-204, QP-207, QP-208 and ES-177 were added in Year 4 and QP-108, QP-131,QP-132, QP-133, QP-147, QP-148, QP-155, QP-160, QP-166 were kept from Year 1 for Year 4 measurements.
Diamond grooved (Gr)	Year 1: 19 Year 2: 7 Year 3: 7 Year 4: 12	QP-110, QP-111, QP-136, QP-138, QP-153, QP-154, QP-156, QP-157, and QP-161 in Years 1 to 3. The first four of these sites (with a total of 12 sections) were overlaid by Year 2. ES-171, ES-172, ES-173, ES-174 were added in Year 4 and QP-103, QP-128, QP-134, QP-153, QP-154, QP-156, QP-157, QP-161 were kept from Year 1 for Year 4 measurements.
Longitudinally broomed (LB)	Year 1: 10 Year 2: 4 Year 3: 4 Year 4: 1	QP-109, QP-112, QP-146, and QP-162. The first two of these sites (with a total of six sections) were overlaid by Year 2. Only QP-162 was kept in Year 4.
Longitudinally tined (LT)	Year 1: 21 Year 2: 21 Year 3: 18 Year 4: 19	QP-100, QP-101, QP-108, QP-117, QP-127, QP-129.1 and QP-129.2, QP-142, and QP-158 in Years 1 to 3. QP-142 was not used in analyses due to high chain wear. ES-178, ES-180, ES-181, QP-187, QP-189, QP-190, QP-191, QP-192, QP-199, QP-201, QP-202, QP-203, QP-205 and QP-206 were added in Year 4 and QP-100, QP-101, QP-117, QP-129 and QP-158 were kept from Year 1 for Year 4 measurements.
Diamond ground continuously reinforced concrete (CRCP-DG)*	Year 4: 1	ES-177
Longitudinally tined continuously reinforced concrete (CRCP-LT)*	Year 4: 4	ES-178, ES-180, ES-181, ES-203

Note: * included in count of texture type sections

In most cases, the field assessment of surface texture type was initially done via a windshield survey at highway speed and then confirmed by observation from the shoulder. The texture type assignment made in Year 1 of the study was checked at the beginning of the Year 4 measurements using photographs taken from the shoulder in the first three years, the Caltrans as-built data base, and field visits. It should be noted that all of the sections classified as burlap drag (BD) were originally constructed before 1977, and it is possible that the BD sections previously had another type of texture that was completely worn off, leaving only the appearance of a BD texture. The longitudinally broomed (LB) pavement surface texture is not commonly found on California highways. As mentioned previously, only one burlap drag section (QP-159) and one longitudinally broomed (QP-162) section, both built as part of the experimental test sections on State Route 58 near Mojave in Kern County in 2003, were measured in Year 4.

Based upon the recommendations of the Quieter Pavement Research Task Group at the start of the Year 3 measurements, the test sections were divided into three surface texture condition categories based on visual observation:

- *New:* defined as a surface that was either open to traffic for less than a year at the time the first measurements were taken in September 2008, or a surface that appeared to have a texture in a condition like new.
- *Aged:* defined as a surface where the wheelpaths showed signs of texture abrasion but the texture was still observable.
- *Worn out:* defined as a surface where traffic had completely worn off the texture from the wheelpaths.

As noted earlier, in the Year 4 experimental design, all of the *worn out* sections were discarded and they were eliminated from the analyses presented in this report. At the time of testing, all of the *new* sections from the Year 3 measurements had been trafficked enough to safely assume they could be categorized as *aged*. Therefore, for those analyses in this final year report that only consider the fourth year of measurements, all of the textures can be considered to be *aged*. But wherever data from multiple years of measurement are considered, a note has been inserted.

The photographs in Figure 2.2 through Figure 2.4 show examples of the different pavement surface types used in the study. Figure 2.5 and Figure 2.6 show examples of burlap-drag and longitudinally tined surfaces in Years 3 and 4, revealing visual changes to the surfaces over that time.

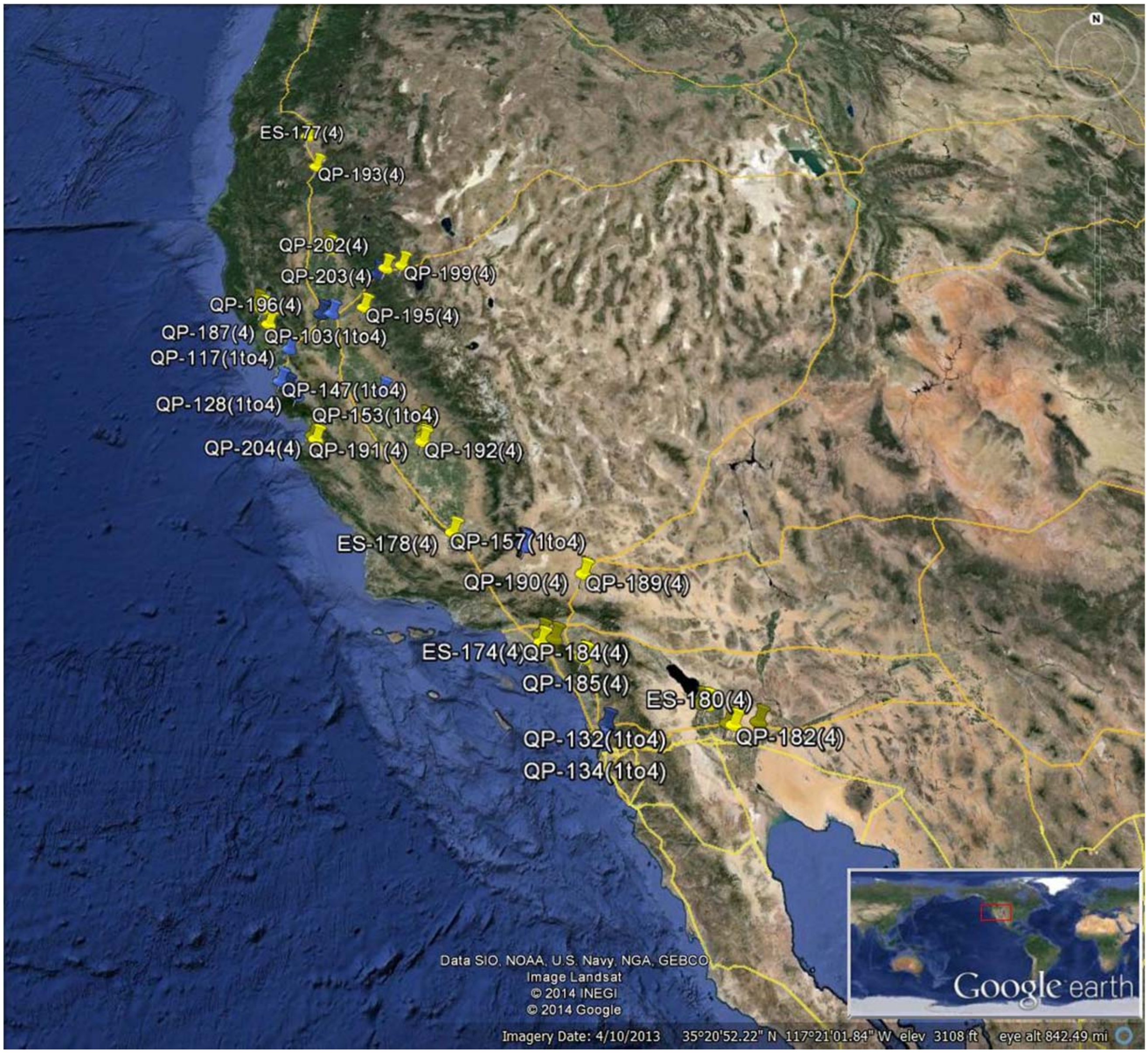


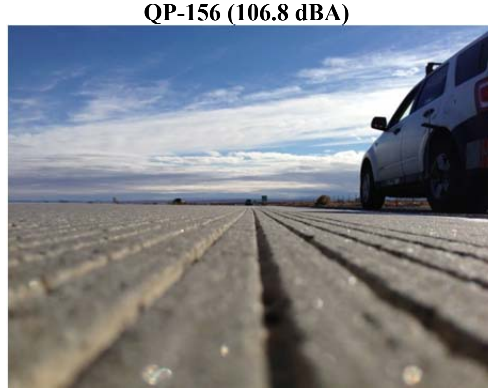
Figure 2.1: Map showing the locations of the sections in Year 4.
(Note: numbers in parenthesis show measurement years and blue pins indicate sites with multiple sections.)
(Note: image obtained using Google™ Earth.)

QP-200 (106.4 dBA) QP-204 (108.6 dBA)

QP-182 (102.9 dBA) QP-197 (102.5 dBA)

Figure 2.2: Example photographs of diamond-ground surfaces and their OBSI levels.

QP-134 (107.6 dBA) QP-156 (106.8 dBA)



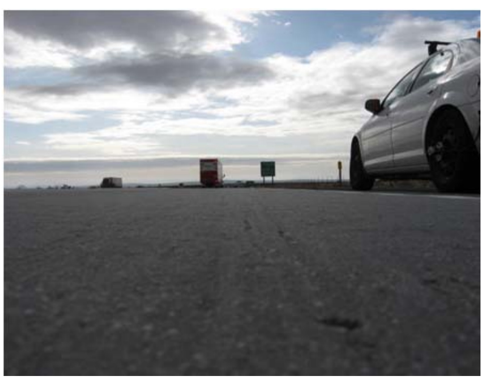
QP-103 (102.9 dBA) QP-154 (104.2 dBA)

Figure 2.3: Example photographs of diamond-grooved surfaces and their OBSI levels.

QP-158 (106.0 dBA) **QP-101 (106.5 dBA)**

ES-180 (101.6 dBA) **ES-178 (111.7 dBA)**

Figure 2.4: Example photographs of longitudinally tined surfaces and their OBSI levels.



QP-159 (101.9 dBA, Year 3) **QP-159 (103.3 dBA, Year 4)**

Figure 2.5: Example photographs of burlap-drag surface QP-159.

QP-162 (102.5 dBA, Year 3) **QP-162 (104.2 dBA, Year 4)**

Figure 2.6: Example photographs of longitudinally broomed surface QP-162.

2.2 Traffic, Rainfall, and Lane Locations of Sections

Traffic data were extracted from Caltrans 2012 annual average daily traffic (AADT) data in the Caltrans traffic database for highways and freeways. Traffic was categorized as *high* if the AADT (two-way) was greater than 32,000 vehicles per day, with smaller amounts categorized as *low*. Rainfall data were determined from annual average California rainfall data from 1960 to 1990 contained in a UCPRC database previously downloaded from the National Climate Data Center, with amounts greater than 620 mm (24.4 inches) categorized as *high* and smaller quantities as *low*. The *high* and *low* traffic and rainfall levels used in Year 4 are the same as those that were used in the asphalt pavement studies *(12)*. Table 2.2 shows the distribution of the sections between the different rainfall and traffic conditions.

Table 2.2: Distribution of Sections by Rainfall and Traffic in Year 4

	Traffic Category		
Rain Category	**High**	**Low**	**Total**
High	9	7	16
Low	22	22	44
Total	**31**	**29**	**60**

Table 2.3 lists the lane locations of the test sections for the fourth year of measurements. It can be seen that most of the test sections are in the outermost lane, and that the remaining test sections are in the innermost lane.

Table 2.3: Lane Locations of Sections Used in Year 4 Measurements

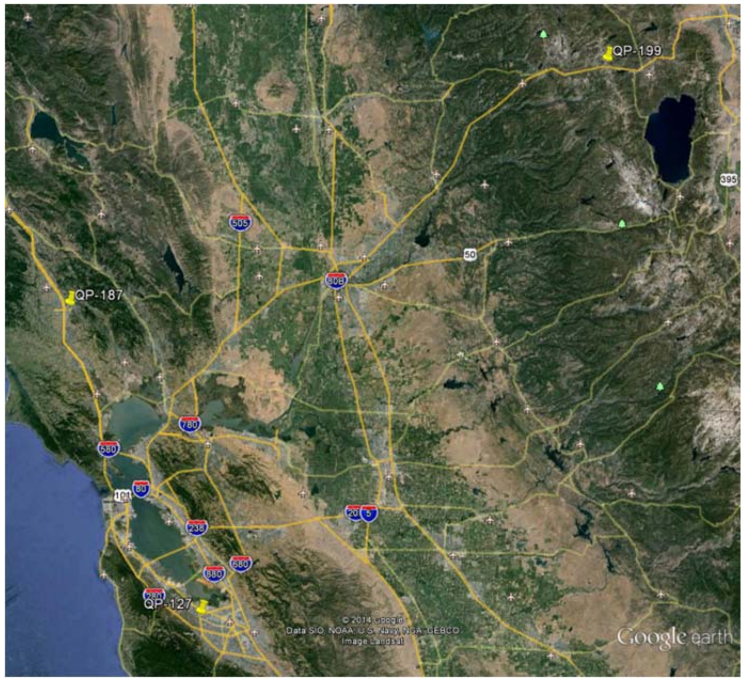
Test Lane and Total Number of Lanes		Number of Sections	
Outermost lane	2 of 2	36	52
	3 of 3	8	
	4 of 4	7	
	5 of 5	1	
Innermost lane	1 of 2	4	8
	1 of 3	2	
	1 of 4	2	

2.3 Joint and Texture Measurement Sections

The fourth year of concrete pavement noise measurements included an effort to study the effects of texture parameters and joint characteristics on sound intensity. This effort included taking field measurements of pavement texture, joint widths and depths, and widths of overbanded sealant on a number of sections. Overbanded sealant is any excess material that rises above the slab tops when crack seal material is placed in a joint. Measurement of joint opening cross-sectional area requires traffic closures. Thirteen pavement sections with a range of surface textures were selected from the study and the texture and joint characteristics of each section were measured. Table 2.4 shows the sections selected for pavement texture and joint characterization. The noise data for QP-127 were extracted from the third year of data collection instead of the fourth year. Figure 2.7(a), (b), and (c) depict the locations of pavement sections selected for texture and joint characterization.

Table 2.4: Pavement Sections for Pavement Texture and Joint Characterization

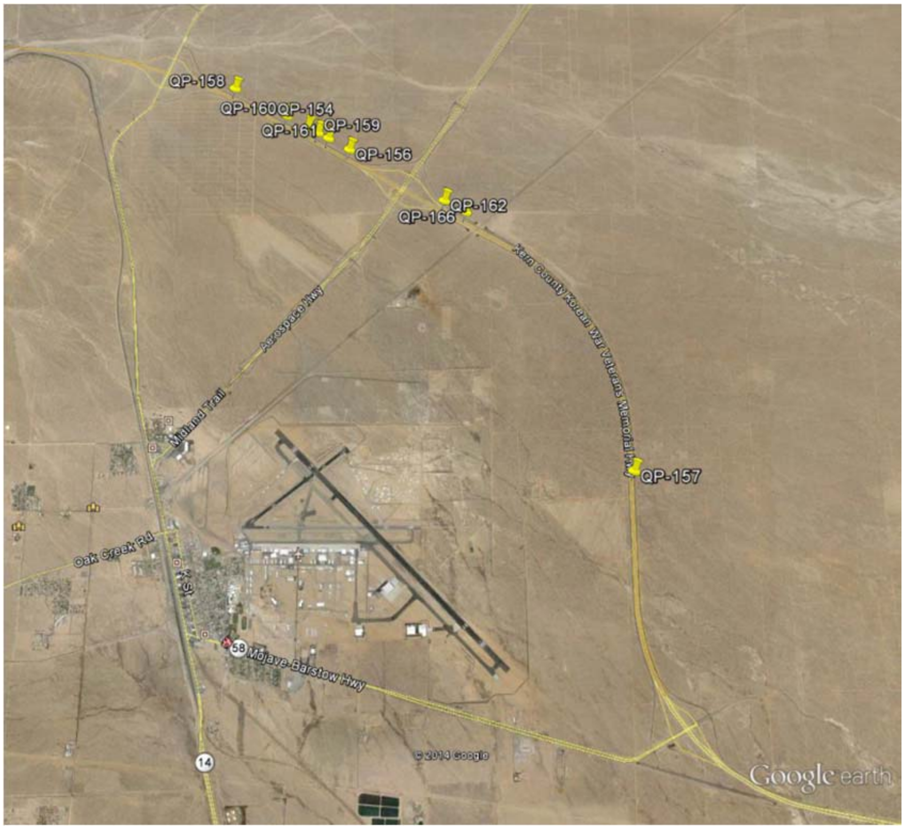
Section	ID	Texture	County	Route	Direction	Postmile	Lane	Date
NEV80-PM5.6	QP-199	LT	NEV	080	EB	5.6	1	10/30/2012
SCL85-PM21.5	QP-127	LT	SCL	085	SB	21.5	1	11/14/2012
SON12-PM16.53	QP-187	LT	SON	012	EB	16.5	2	11/15/2012
KER-058-PM109.5	QP-158	LT	KER	058	EB	109.5	2	02/11/2013
KER-058-PM110.0	QP-160	DG	KER	058	EB	110.0	2	02/11/2013
KER-058-PM110.2	QP-154	Gr	KER	058	EB	110.2	2	02/11/2013
KER-058-PM110.3	QP-159	BD	KER	058	EB	110.3	2	2/12/2013
KER-058-PM110.3	QP-161	Gr	KER	058	EB	110.3	2	2/12/2013
KER-058-PM110.6	QP-155	DG	KER	058	EB	110.6	2	2/12/2013
KER-058-PM111.2	QP-156	Gr	KER	058	EB	111.2	2	2/13/2013
KER-058-PM111.4	QP-157	Gr	KER	058	EB	111.4	2	2/13/2013
KER-058-PM111.5	QP-162	LB	KER	058	EB	111.5	2	2/13/2013
KER-058-PM111.7	QP-166	DG	KER	058	EB	111.6	2	2/13/2013


QP-199
QP-187
QP-127
Google earth

(a)


Klamath Mountains
Black Rock Desert
Great Salt Lake
Nevada
Sierra Nevada Mountains
California
QP-158(1to4)
QP-157(1to4)

(b)



(c)

Figure 2.7: Locations of pavement sections for pavement texture characterization: (a) northern California, (b) southern California, and (c) detail of southern California locations on State Route 58.
(Note: images obtained using Google™ Earth.)

3 DATA COLLECTION AND REDUCTION METHODS

3.1 Data Collection Methods

Tire/pavement noise was measured in terms of sound intensity using the on-board sound intensity (OBSI) method and pavement roughness was measured in terms of the International Roughness Index (IRI) using a wide-spot (RoLine^{TM}) laser. Roughness was only measured in the fourth year of the study after the wide-spot laser was installed on the measurement vehicle. Macrotexture was measured both in terms of Mean Profile Depth (MPD), using a laser texture scanner (LTS), and in terms of Mean Texture Depth (MTD), which is very similar to MPD, using the sand patch method. The outflow meter was used to measure the potential for hydroplaning. Joint dimensions were measured and three-dimensional scans of the pavement surface were used to calculate various texture parameters.

3.1.1 On-Board Sound Intensity

On-board sound intensity (OBSI) data was collected as specified in AASHTO TP-76-09 (*1*). Data were gathered on each section using three passes of five-second duration at 60 mph (96 km/hr), following the typical OBSI procedure that was also used in all other California Quieter Pavement Research (QPR) studies. The data quality procedures incorporated into the AASHTO protocol were verified at the beginning and the end of testing on each site. The instrumented vehicle used for the fourth year of measurements is shown in Figure 3.1. A different vehicle mounted with the same OBSI equipment was used in previous years.

The OBSI method requires the measurement of sound intensity levels in one-third octave bands, from the frequency centered at 400 Hz to the frequency centered at 5,000 Hz. These values are obtained at the leading and the trailing edges of the tire contact patch. Three repeated passes are conducted at each test section to account for lateral variability of the path of the test vehicle and minor deviations from the 60 mph (96 km/hr) specification. Measurements from the three passes at the two probe locations are used to obtain noise spectra, which are in turn used to calculate the overall sound intensity level, the single value that summarizes the overall tire/pavement noise.

The sound analyzer for the OBSI measurements was programmed to collect five-second periods of data at each test site. In the first year of the four-year study, an additional pass with data collected in 15 millisecond intervals was performed in order to try to identify the effects of joints and nonhomogeneity along each section (*2*). Some initial analysis was also performed regarding the effects of joint slap and of faulting and sealing of the joints on the overall OBSI measurements, and the analysis of these joint effects on OBSI levels was summarized in the report on the first two years of this study (*2*). Field measurements under traffic closures that were necessary to isolate the effects of joints on OBSI were part of the fourth year test plan for this study and are included in this report. The dimensions of joints were measured in the field, and the effect of joint slap was calculated using the procedure developed by Donavan that is documented on the American Concrete Pavement Association (ACPA) website (*3*).

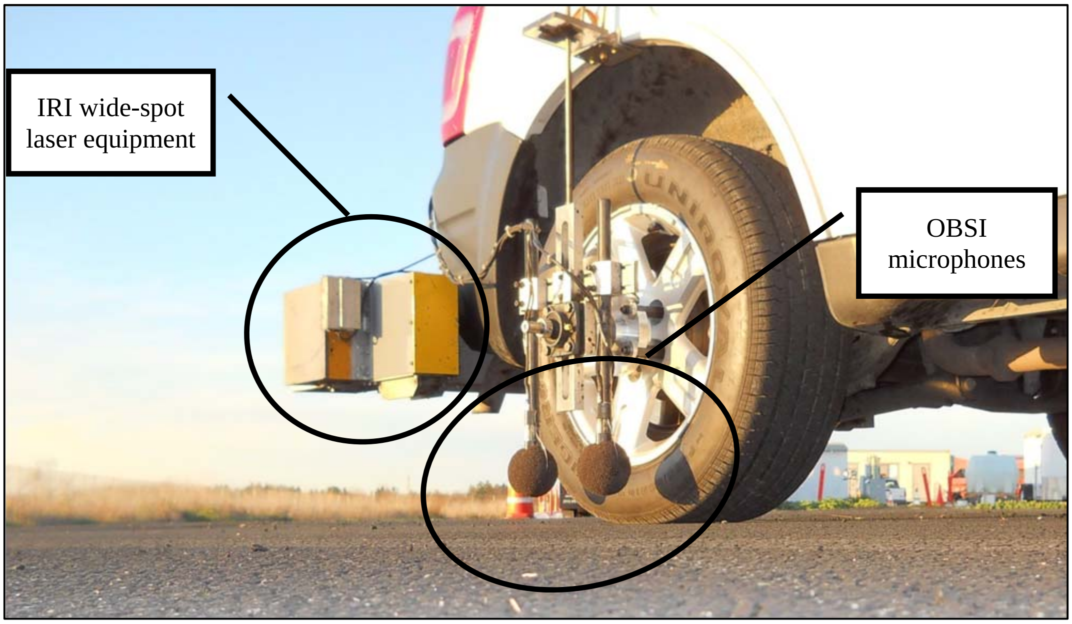


Figure 3.1: The UCPRC OBSI and IRI test vehicle with mounted microphones and laser equipment.

3.1.2 Laser Texture Scanner

The laser texture scanner (LTS) (Figure 3.2) measures pavement surface macrotexture, scanning the surface profile of an area three inches wide by four inches long (75 mm by 100 mm). Manufactured by Ames Engineering, the LTS has a laser dot size of approximately 0.050 mm, a vertical sample resolution of 0.015 mm, and a horizontal sample spacing of 0.015 mm. In this study, the LTS was used to measure the MPD (ASTM E1845-09) of the surface of each pavement section.

3.1.3 Sand Patch Test

The sand patch test (ASTM E965-15) is undertaken on any dry surface by spreading a known quantity of sand or any particulate fine-grain materials with uniform gradation, e.g., glass beads, on the surface. The material is then evenly distributed over a circular area to bring it flush with the highest aggregate peaks. The diameter of this circle is measured at four different evenly spaced angles, and then averaged. By knowing the test material volume and diameter of the circle, MTD (ASTM E1845-09) can easily be calculated.

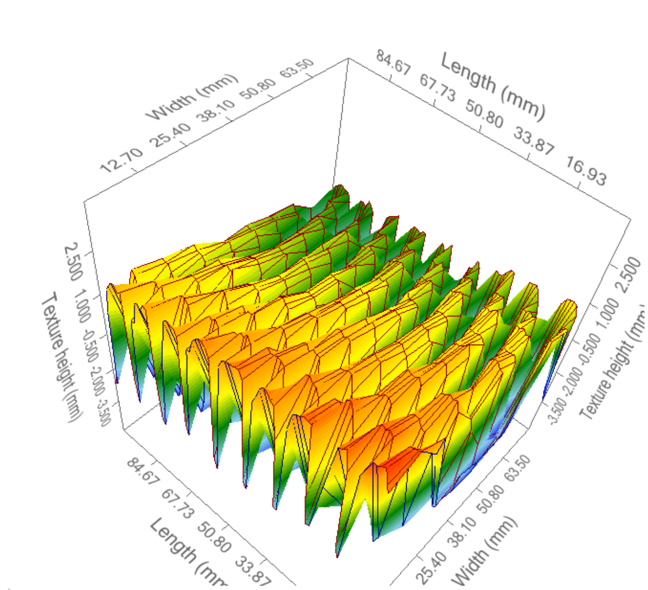


Figure 3.2: Laser texture scanner and an example of surface texture profile it measured (Section QP-158 with longitudinally tined texture).
(Photo of LTS courtesy of Ames Engineering, Inc.)

The values of MPD and MTD differ due to the definitions of MPD, which is a two-dimensional geometric measure, and MTD, which is defined on a three-dimensional surface that also considers the glass bead size used in the test. A linear transformation of the Mean Profile Depth from a profiler can provide an estimate of the Mean Texture Depth measured according to the sand patch test (ASTM E965-15). ASTM E1845 provides an equation for calculating the Estimated Texture Depth (ETD), which is the same as Mean Texture Depth, from MPD as shown *(4)*:

ETD (mm) = 0.8MPD (mm) + 0.2

3.1.4 Outflow Meter

The outflow meter (OFM) (Figure 3.3) is a device that measures the rate at which a known quantity of water, under gravitational pull, escapes through voids in the pavement texture of the structure being tested. The time required for the water to run out is referred to as *outflow time.* Use of the OFM provides a measure of a pavement’s ability to relieve pressure from under vehicle tires, which provides an indication of the potential for hydroplaning under wet conditions. The reciprocal of the outflow time is highly correlated with MPD except when a surface is highly porous. The OFM can also be used to detect surface wear and predict correction measures.

Figure 3.3: Outflow meter.
(Courtesy of KLARUW Systems)

3.1.5 Joint Characteristic Measurement

Joint widths and depths were measured using a scale or tape measure, and fault heights were measured for each section using a straightedge as the measuring device. The condition of the joints was also documented (sealed/unsealed). The width, depth, and fault height of all the joints in a section were measured in the left wheelpath, in the right wheelpath, and halfway between the wheelpaths.

3.1.6 Testing Program on Each Section for Texture and Joint Condition

Table 3.1 shows the testing program of the experimental field sections for texture and joint characterization.

Table 3.1: Testing Programs for Pavement Texture and Joint Characterization

Measurement	Parameter	Device	Spacing	Lateral
Macrotexture	MPD	LTS	25 m	Right and between wheelpath
Macrotexture	Time	Outflow meter	25 m	Right and between wheelpath
Macrotexture	MTD	Sand patch	Four evenly distributed measurements around circle of sand	Right and between wheelpath
Joint characteristics	Width, depth, fault	straightedge	All joints in the section	Left, right and between wheelpath

3.2 OBSI Data Reduction

For OBSI data reduction, the sound intensity levels at the leading and trailing edges are averaged through the energy method. The energy average is obtained using the following equation:

$$Energy\ average = 10 * log_{10}\left[\frac{1}{n} \times \sum_{i=1}^{n} 10^{\frac{x_i}{10}}\right]$$

where x_i are the sound intensity values to be averaged, in this case the one-third octave results at the two probe locations, and n is the number of samples, which in this case is two. The arithmetic mean is then used to average the three passes.

An air density correction was applied to take into account the effect of air density on the speed of sound, which is calculated from data on atmospheric variables collected during testing, including air temperature, barometric pressure, and relative humidity, as well as the altitude of the section.

The UCPRC changed tires periodically as they underwent aging and wear during testing campaigns. In the fourth year of noise data collection on concrete pavements, Standard Reference Test Tire 5 (SRTT#5) was used for all measurements. Linear transformation equations were developed using only concrete test sections in order to adjust the results gathered using different tires in Years 1, 2, 3, and 4 back to the first SRTT (SRTT#1) used by the UCPRC research team. Other adjustments were made to the data in order to convert values from the two Larson Davis two-channel analyzers used in the first year of concrete pavement noise testing to the Sinus Harmonie (hereafter referred to as Harmonie) four-channel analyzer used in Years 2, 3, and 4. The details of the development of these tire and analyzer conversion factors are included in Appendix B. All the OBSI values shown in this report have been adjusted to equivalent values with SRTT#1 and the Harmonie analyzer.

It should be noted that no temperature correction has been applied to the data in this report. Earlier UCPRC-developed corrections for air temperature based on testing at two sites *(5)* have not been included in the calculations in this report because the effect of air temperature was considered too small for multiyear measurements.

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4 TEST RESULTS

The details of all of the test sections, including their classification into the five surface textures, last surface construction dates, ages at time of measurements and overall OBSI measurement for each year and IRI in the fourth year are presented in Appendix A, sorted by texture type. Table 4.1 summarizes the OBSI and IRI results by texture type. Additional test result details regarding OBSI, IRI, and other test values are presented in succeeding subsections of this chapter.

4.1 Overall Sound Intensity and Spectral Content Results by Texture Type

Plots of OBSI for individual test sections for each of the four years of measurement, ordered by texture type and OBSI level, are shown in Appendix C. In the following subsections of this chapter, overall OBSI and OBSI spectral contents are plotted showing data from the Year 4 factorial. Also shown are changes in overall OBSI and OBSI spectral content over time for those sections where four years of measurements were available. The data for sections not included in Year 4 of the data collection can be found in previous reports.

4.1.1 Diamond-Ground Sections

The overall OBSI noise measurement results for the diamond-ground sections are shown in Figure 4.1, ordered by section number. (*Note:* an examination of Section QP-193 in Siskiyou County revealed that it had excessive chain wear and therefore abnormally high sound intensity values; as a result it was excluded from the analyses in this report.) Of the 27 diamond-ground sections measured in Year 4, eight had also been measured over the previous three years. At the time of measurement in the first three years of testing, the DG sections ranged in age since last retexturing from 0.3 to 13.4 years, and in the fourth year of testing they ranged from 0.3 to 15.5 years. In the fourth year of measurements, the interquartile ranges, which indicate the range of the middle 50 percent of the measurements, fell between 103.5 and 106.3 dBA.

Figure 4.2 shows the average overall OBSI for the eight DG sections with four years of measurements, and it indicates that the overall sound intensity of the diamond-ground sections generally increased with age, with an average increase for the set of 0.8 dBA per year across the four years.

Figure 4.3 shows the average OBSI spectral content in each year for the eight DG sections with four years of measurements and indicates that low-pitched noise increased over time while noise at higher frequencies remained relatively constant. Figure 4.4 shows the average, maximum, and minimum OBSI values for each one-third octave frequency for all 27 sections measured in the fourth year, and it reveals a peak at 800 to 1,000 Hz, reduced noise for all frequencies moving away from the peak, and a broader range of noise at lower frequencies than at higher frequencies.

Table 4.1: Summary of Average and Range of OBSI and IRI for Each Texture Type across Four Years of Measurement

Texture Type	Texture Condition	Year 1			Year 2			Year 3			Year 4			
		No. of Sections	Range OBSI (dBA)[2]	Avg. OBSI (dBA)[1]	No. of Sections	Range OBSI (dBA)[2]	Avg. OBSI (dBA)[1]	No. of Sections	Range OBSI (dBA)[2]	Avg. OBSI (dBA)[1]	No. of Sections	Range OBSI (dBA)[2]	Avg. OBSI (dBA)[1]	Avg. IRI[3] (in/mi)
DG	New	6	99.7 to 107.1	103.8	6	102.3 to 107.1	104.7 (104.7)	4	102.4 to 107.5	104.8	4	101.6 to 112.0	105.5	68.1
	Aged	26			18			23			23			
	Worn	0			0			0			0			
Gr	New	0	102.1 to 105.6	104.3	0	103.6 to 106.2	104.9	0	104.3 to 107.2	105.8	0	103.1 to 106.8	104.8	81.2
	Aged	19			7			7			12			
	Worn	0			0			0			0			
LT	New	6	103.1 to 106.3 (101.3 to 103.8)	104.5	6	105.1 to 106.4 (105.0 to 106.6)	105.1	0	104.9 to 106.1 (104.8 to 105.9)	105.6	3	103.8 to 110.3	105.3	95.8
	Aged	12			12			18			16			
	Worn	3			3			3			0			
BD	New	0	101.2 to 106.3 (102.6 to 104.4	104.2	0	102.8 to 107.5 (102.8 to 105.6)	105.3	0	102.8 to 107.6 (103.9 to 105.9	105.6	0	NA	103.1	65.0
	Aged	10			7			7			1			
	Worn	27			24			24			0			
LB	New	0	101.3 to 106.4 (101.3 to 103.8)	103.7	0	102.6 to 103.4	103.0	0	103.1 to 104.4	103.6	0	NA	104.2	89.0
	Aged	4			4			4			1			
	Worn	6			0			0			0			

Notes:
[1] New and aged sections only (all sections shown in parentheses if there are also worn out sections).
[2] New and aged sections only (all sections shown in parentheses if there are also worn out sections).
[3] IRI was only measured in Year 4 when wide-spot laser was installed.

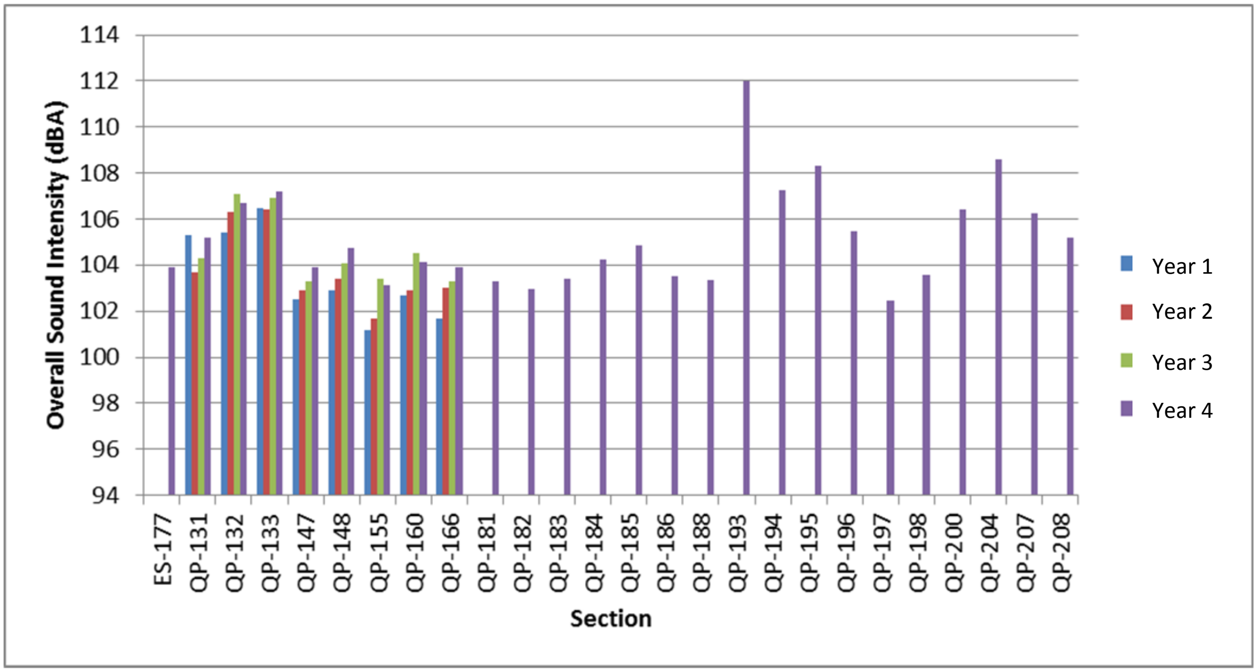

Figure 4.1: Overall sound intensity for all 27 diamond-ground (DG) sections over four years.

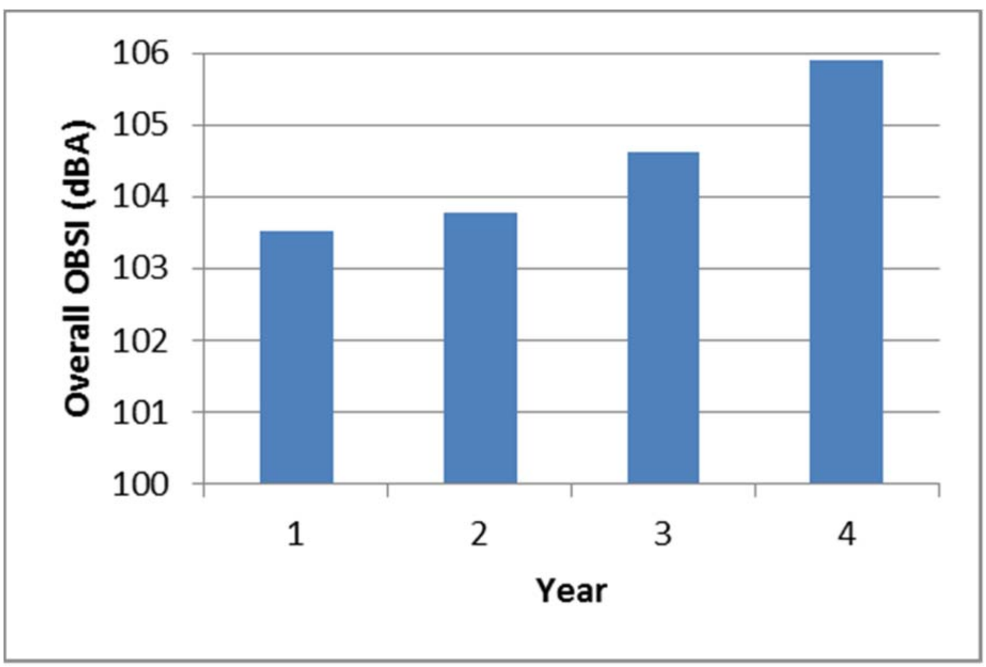

Figure 4.2: Average overall sound intensity for diamond-ground sections over four years of measurement for eight DG sections.

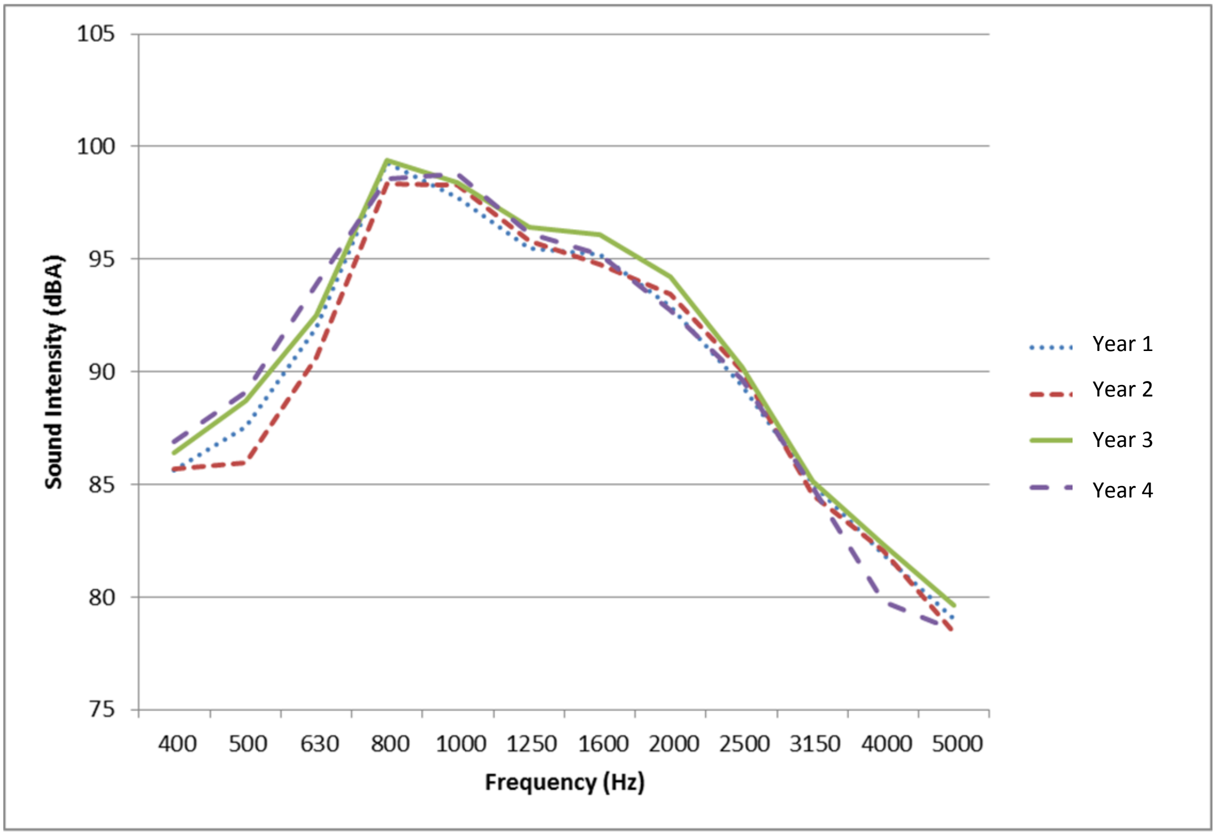

Figure 4.3: Change in average OBSI spectral content for eight diamond-ground (DG) sections over four years of measurement.

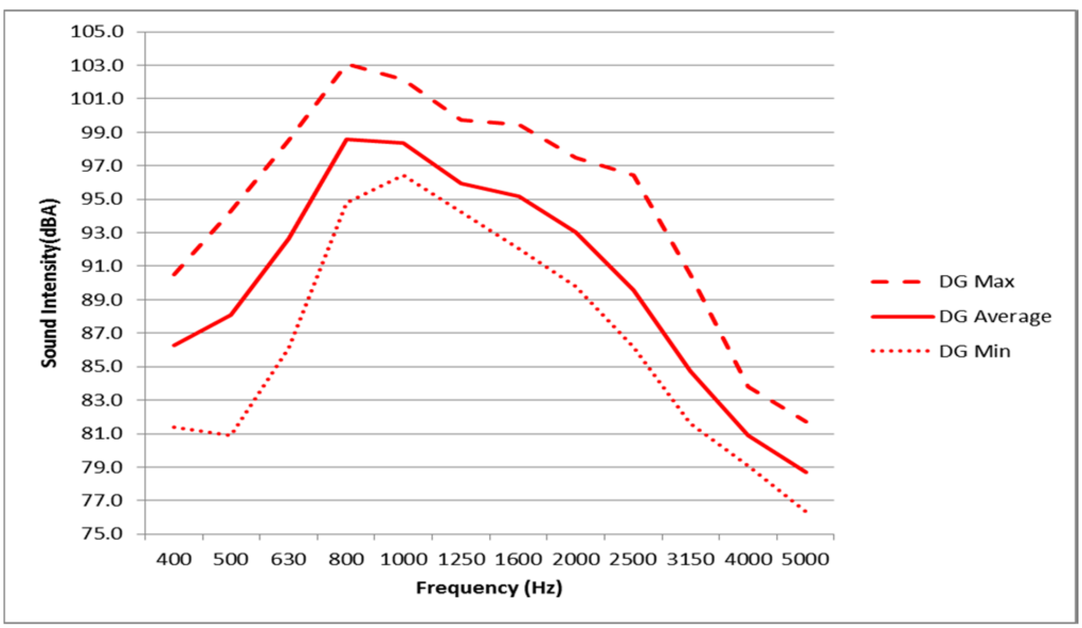

Figure 4.4: Average, maximum, and minimum values of OBSI spectral content frequencies for 27 diamond-ground (DG) sections measured in fourth year.

4.1.2 *Diamond-Grooved Sections*

The overall OBSI noise measurement results for the diamond-grooved sections are shown in Figure 4.5, ordered by section number. Of the 12 diamond-grooved sections measured in Year 4, seven had also been measured over the previous three years. The Gr sections ranged in age since last retexturing from 2.0 to 4.7 years at the time of measurement in the first three years of testing, and 5.4 to 12.2 years in the fourth year of testing. The interquartile ranges, which indicate the range of the middle 50 percent of the measurements, fell between 104.6 and 106.8 dBA in the fourth year of measurement.

Figure 4.6 shows the average overall OBSI for the seven Gr sections with four years of measurements, and it indicates that the overall sound intensity of the diamond-ground sections generally increased with age, with an average increase for the set of 0.3 dBA per year over the four years of measurements.

Figure 4.7 shows the average OBSI spectral content in each year for the seven Gr sections with four years of measurements and indicates that low-pitched noise increased over time while noise at higher frequencies remained relatively constant after an initial increase between Year 1 and Year 2. Figure 4.8 shows the average, maximum, and minimum OBSI values for each one-third octave frequency for all twelve sections measured in the fourth year, and it reveals a peak at 800 Hz and reduced noise for all frequencies moving away from the peak, with similar ranges between the maximum and minimum noise levels across all frequencies.

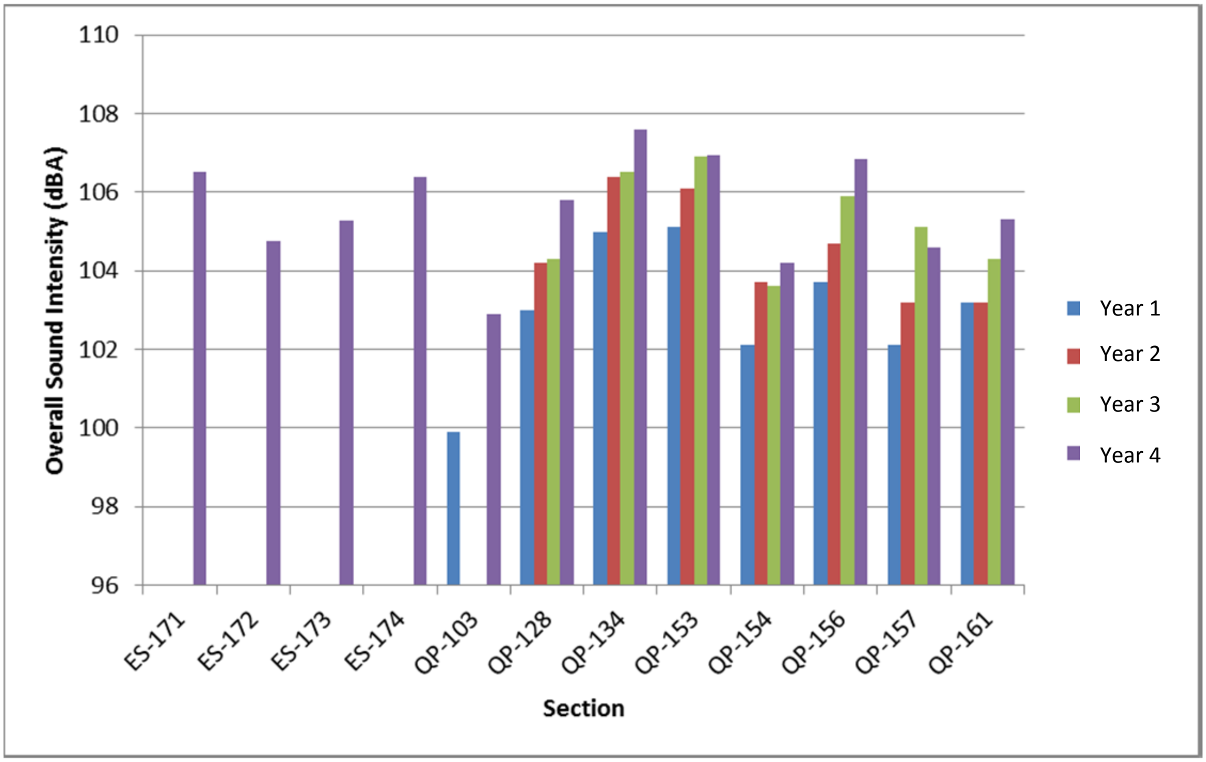

Figure 4.5: Overall sound intensity for all 12 diamond-grooved (Gr) sections over four years.

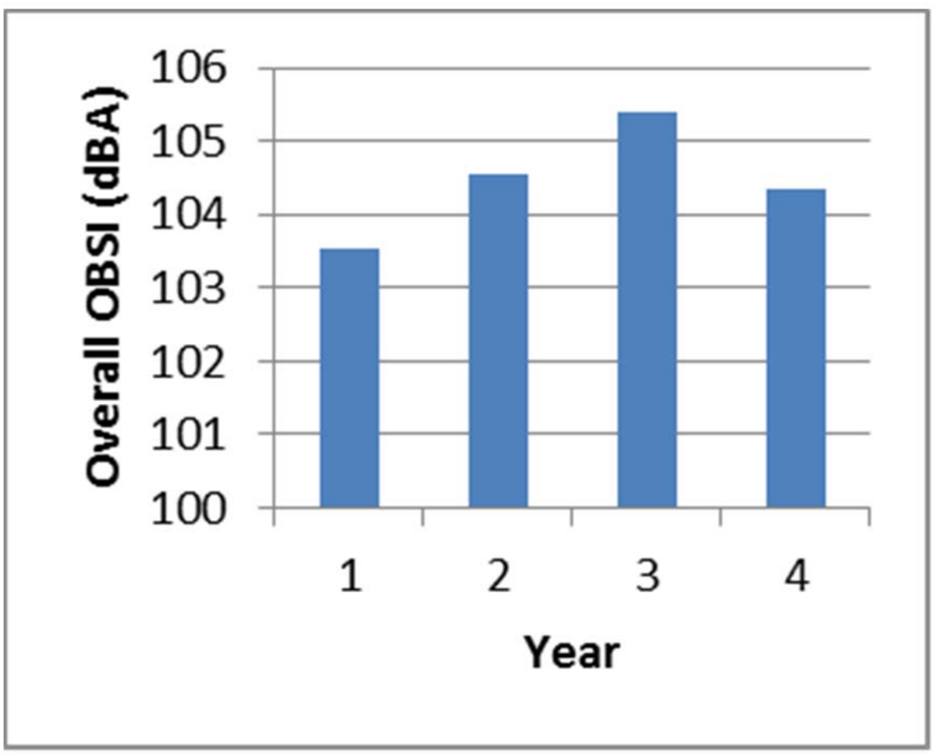

Figure 4.6: Average overall sound intensity for seven diamond-grooved (Gr) sections over four years of measurement.

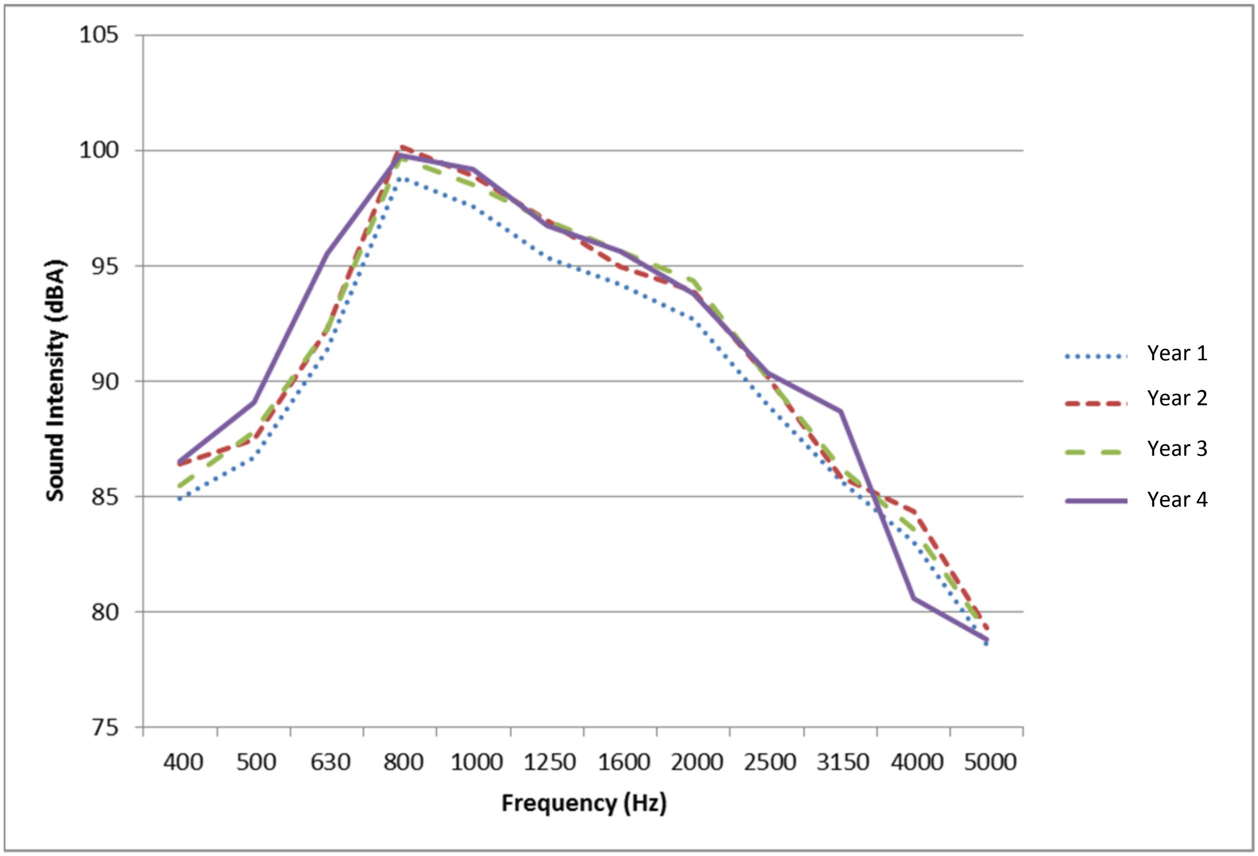

Figure 4.7: Change in average OBSI spectral content for seven diamond-ground (Gr) sections over four years of measurement.

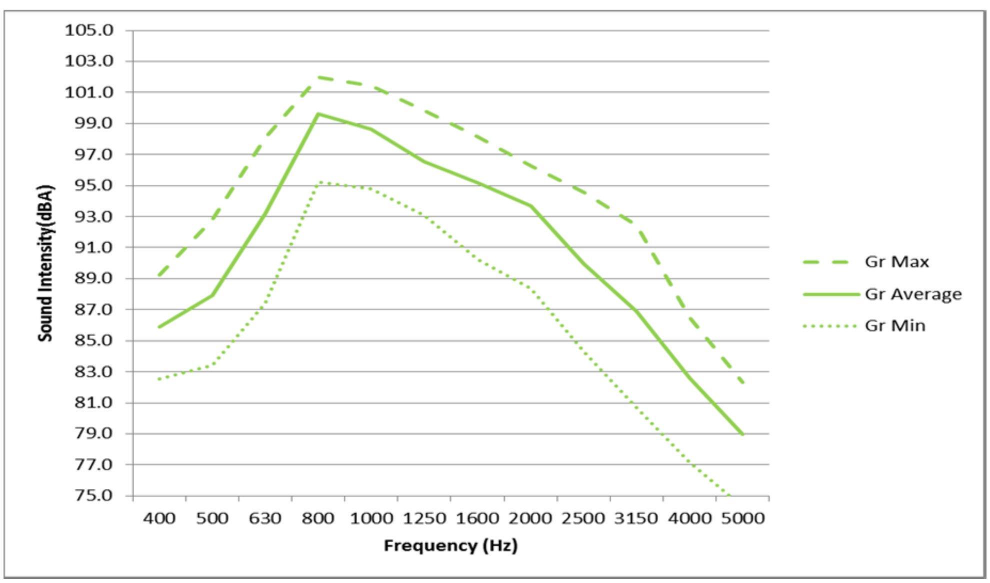

Figure 4.8: Average, maximum, and minimum values of OBSI spectral content frequencies for 12 diamond-grooved (Gr) sections measured in fourth year.

4.1.3 Longitudinally Tined Sections

The overall OBSI noise measurement results for the longitudinally tined sections are shown in Figure 4.9, ordered by section number. Of the 20 longitudinally tined sections measured in Year 4, six had also been measured over the previous three years. The LT sections ranged in age since last retexturing from 0.3 to 45.8 years at the time of measurement in the first three years of testing, and from 1.0 to 36.5 years in the fourth year of testing. The interquartile ranges, which indicate the range of the middle 50 percent of the measurements, fell between 104.3 and 106.5 dBA in the fourth year of measurement.

Figure 4.10 shows the average overall OBSI for the six LT with four years of measurements, and it indicates that the overall sound intensity of the longitudinally tined sections generally increased with age, with an average increase for the set of 0.1 dBA per year over the four years of measurements.

Figure 4.11 shows the average OBSI spectral content in each year for the six LT sections with four years of measurements and indicates that low-pitched noise increased over time while noise at higher frequencies remained relatively constant after an initial increase between Year 1 and Year 2. Figure 4.12 shows the average, maximum, and minimum OBSI values for each one-third octave frequency for all twenty sections measured in the fourth year, and it reveals a peak at 800 Hz to 1,000 Hz and reduced noise for all frequencies moving away from the peak, and a relatively high level of noise between 1,600 and 2,000 Hz. There is greater variability between the maximum and minimum noise levels at lower frequencies.

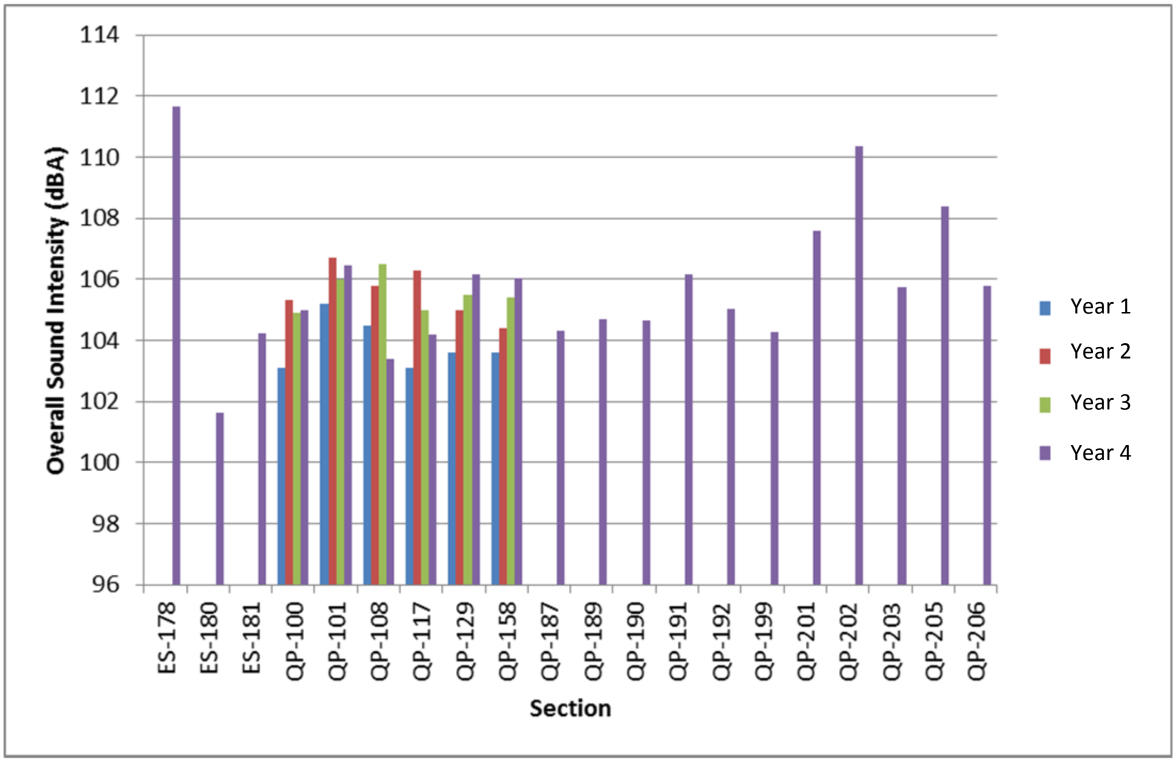

Figure 4.9: Overall sound intensity for all 20 longitudinally tined (LT) sections included in the fourth year.

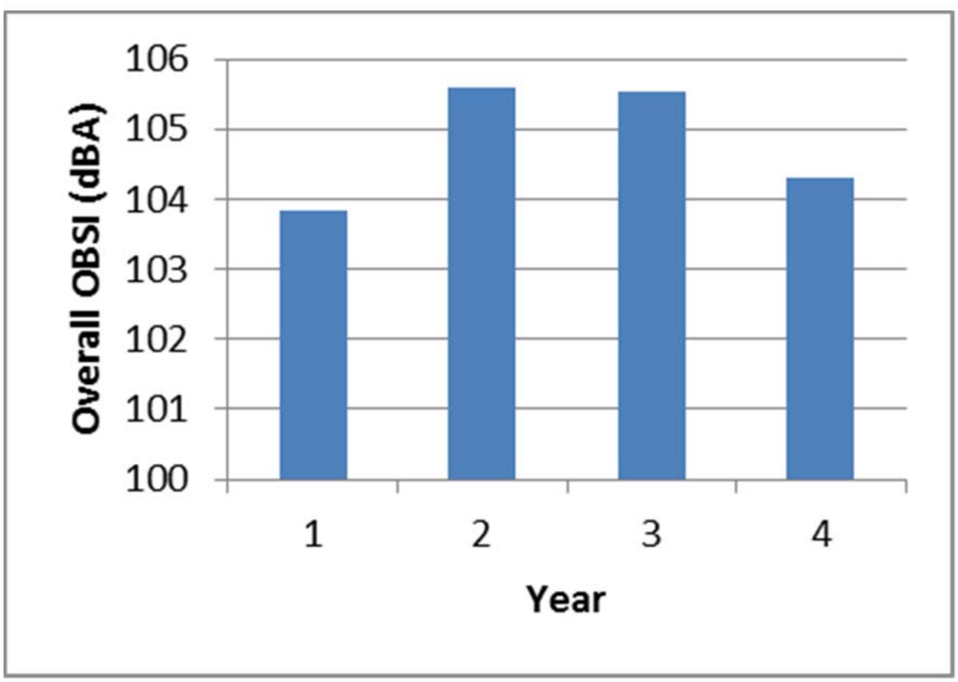

Figure 4.10: Average overall sound intensity for six longitudinally tined (LT) sections over four years of measurement.

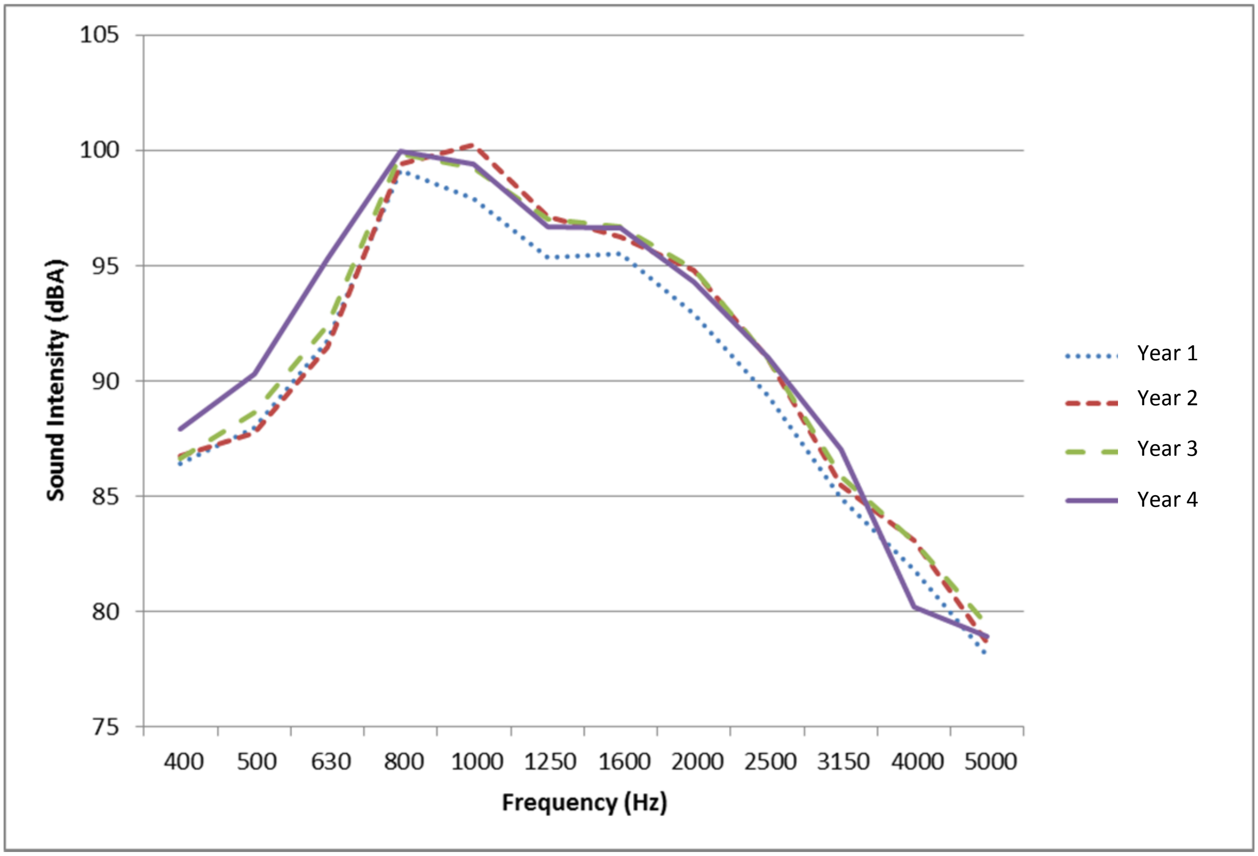

Figure 4.11: Change in average OBSI spectral content for six longitudinally timed (LT) sections over four years of measurement.

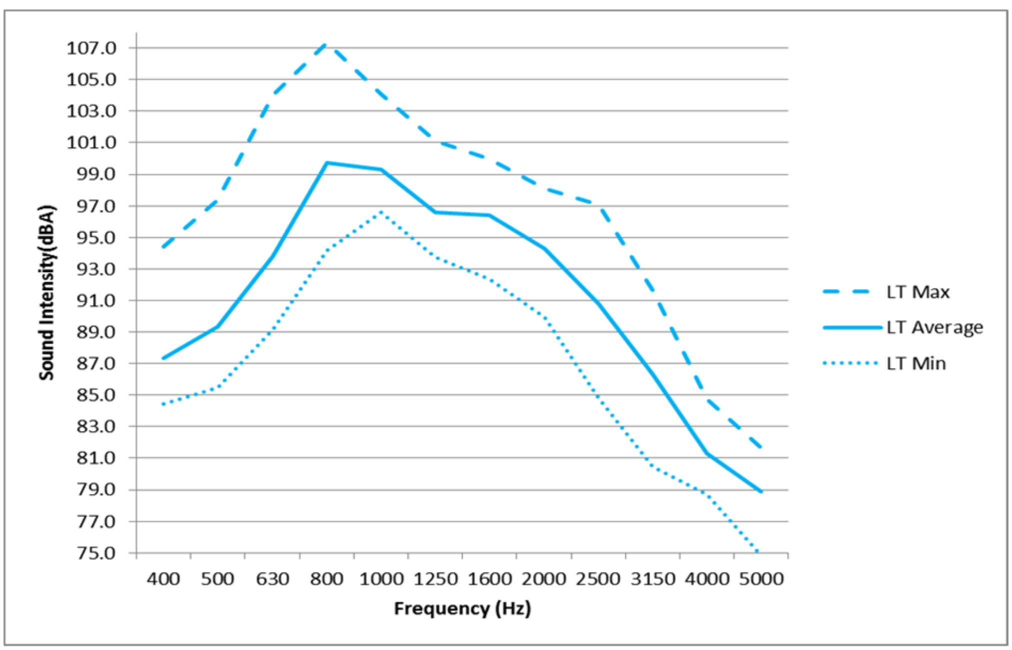

Figure 4.12: Average OBSI spectral content for 20 longitudinally tined (LT) sections over four years.

4.1.4 Burlap-Drag Section and Longitudinally Broomed Section at Kern 58 Mojave Test Site

The only burlap-drag section included in the fourth year study was QP-159—on State Route 58 in Kern County near Mojave—and it was 9.1 years old at the time of the fourth year measurement. The spectral content for each year and the overall sound intensity for each year for that section are shown in Figure 4.13 and Figure 4.14, respectively. The former figure shows that the maximum sound intensity observed for this burlap-drag section occurred at 800 Hz, and it can be seen that most of the increase in noise over the four years occurred at frequencies below that peak. Similar to the LT sections, the noise at 1,600 Hz is relatively high.

The only longitudinally broomed section included in the fourth year measurements was QP-162, which was 10.3 years old at the time of the fourth year measurements, and was also part of the Mojave test sections. The spectral content for each year and the overall sound intensity for each year are shown in Figure 4.15 and Figure 4.16, respectively. The maximum sound intensity observed for the longitudinally broomed section occurred at both 800 Hz and 1,600 Hz, which indicates that the sound pressure is quite high at 1,600 Hz since this frequency has a lower A-weighting than that of 800 Hz and 1,000 Hz. It is not known why the double peak noise spectrum pattern occurred. It appears that the increases in noise generally occurred across all frequencies.

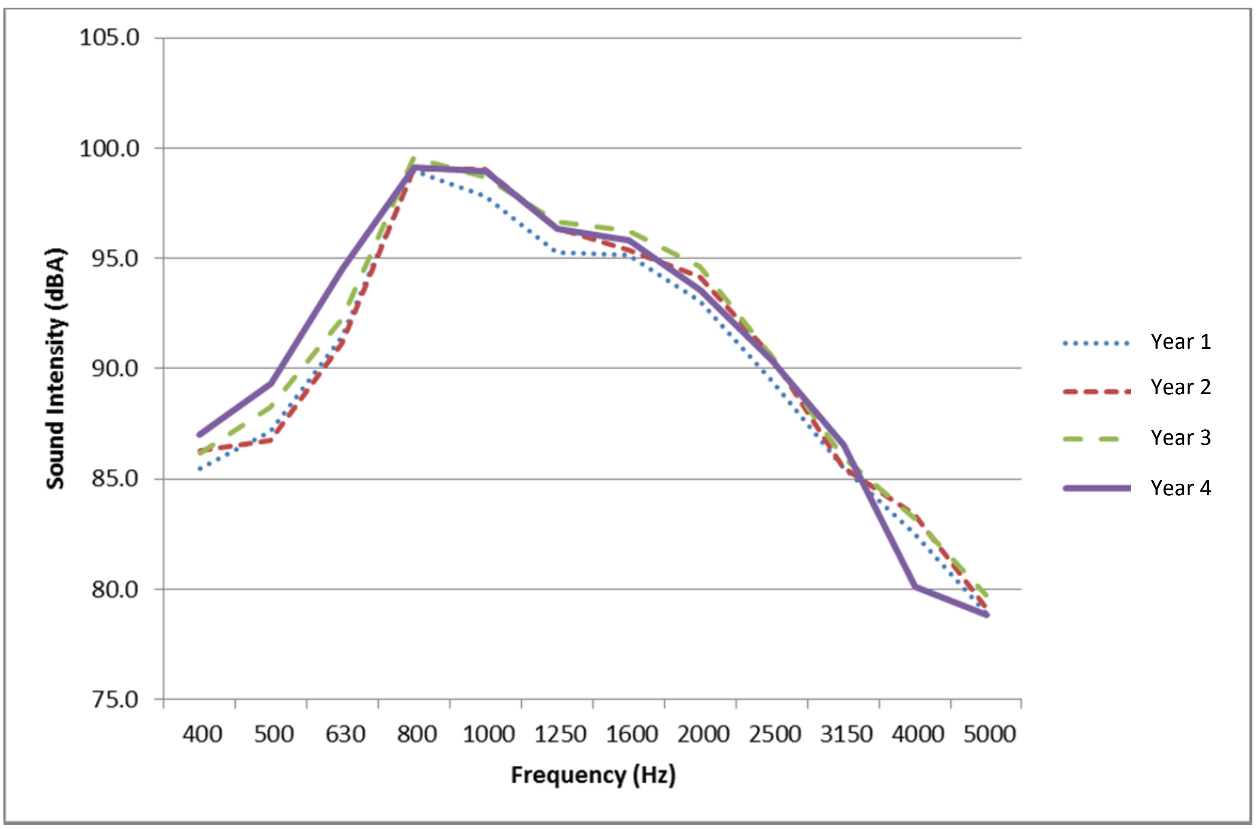

Figure 4.13: OBSI spectral content for the burlap-drag (BD) section over four years of measurement.

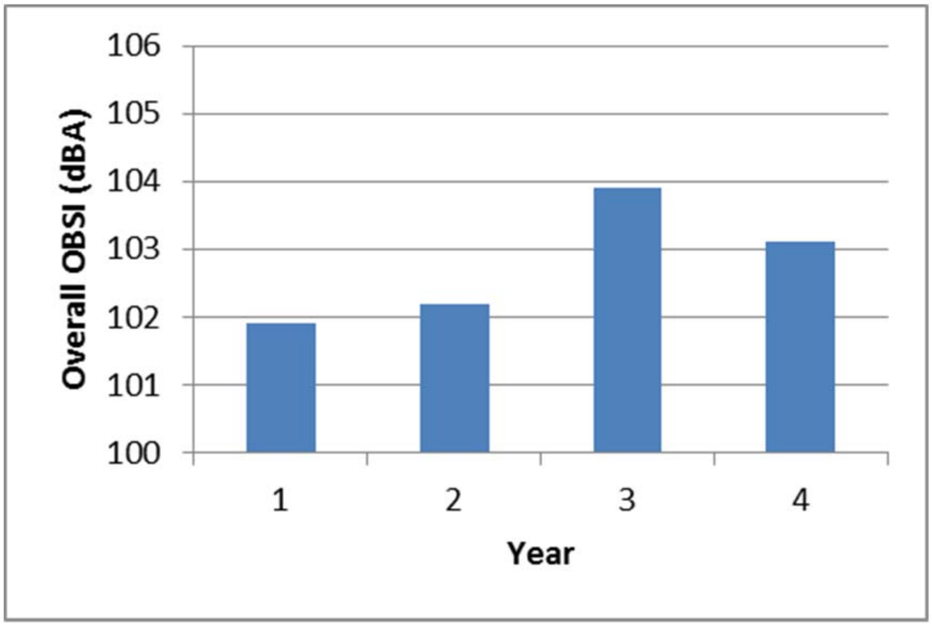

Figure 4.14: Overall sound intensity for the burlap-drag (BD) section over four years of measurement.

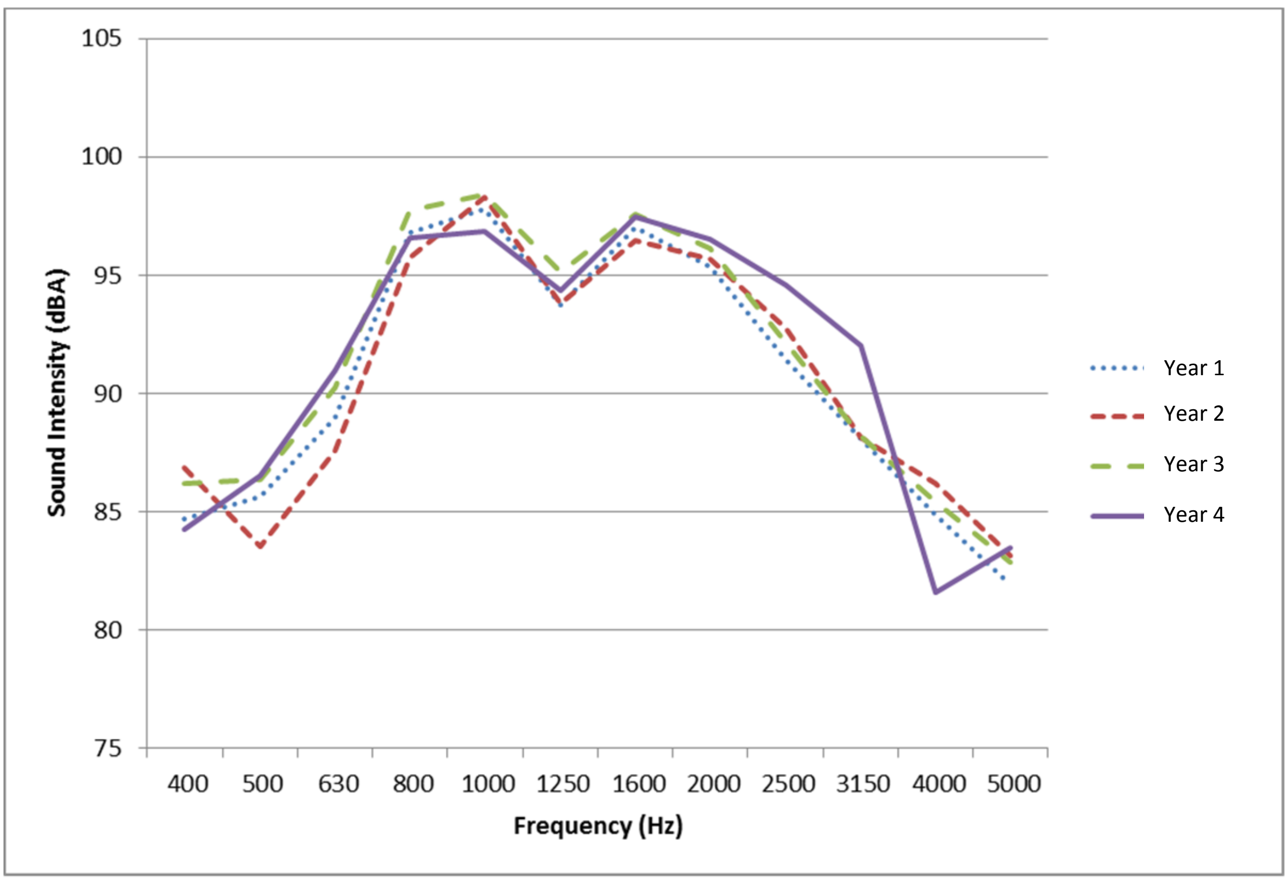

Figure 4.15: OBSI spectral content for the longitudinally broomed (LB) section over four years of measurement.

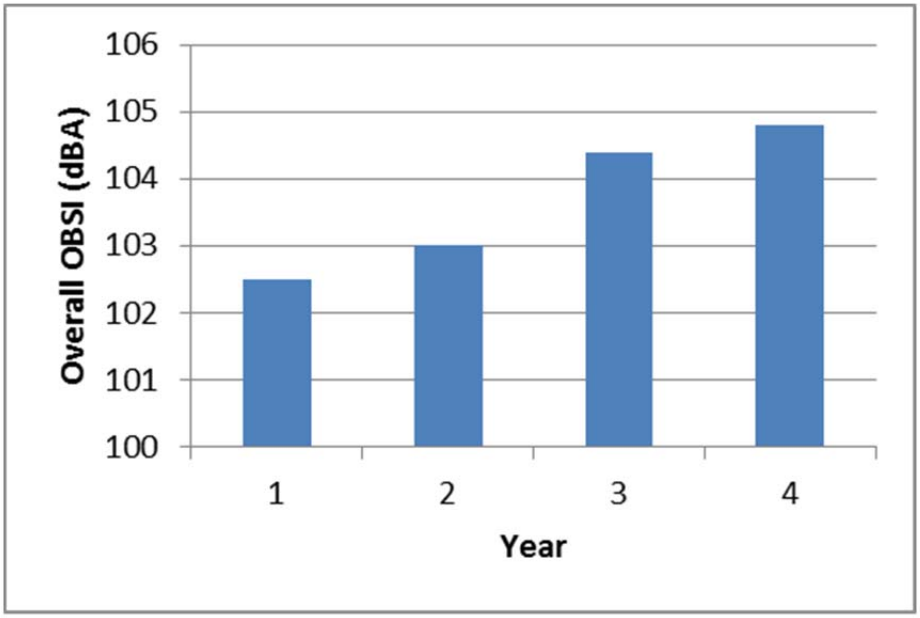

Figure 4.16: Overall sound intensity for the longitudinally broomed (LB) section over four years of measurement.

4.2 IRI Measurements

Although IRI was not the primary focus of this project, it was measured in order to understand its potential effect on tire/pavement noise and to provide an indication of the levels of smoothness (the opposite of roughness) that occur for the different surface treatments. It should be remembered that the results presented in this report are for a very small sample of all of the uses of these textures on concrete pavements in California, and they are intended to only provide an indication for the sections measured for noise and not to provide a comprehensive view of the smoothness that can be achieved or to suggest anything about their longer-term performance.

Plots of IRI for individual test sections for each of the four years of measurement, ordered by texture type and IRI level, are shown in Appendix C. The IRI measurements for each section are shown in Appendix A.

Table 4.2 provides summary statistics for the roughness on the fourth year test sections. As mentioned previously, IRI was only measured in the fourth year of the study when the wide-spot laser was installed on the noise-measuring vehicle. The wide-spot laser was necessary because it provides a sufficiently large measurement width compared to a standard profiler laser so that the directional concrete texture that can produce an incorrect (rougher) estimate of concrete pavement IRI is removed from the profile.

Table 4.2: Summary of Average, Range, and Interquartile Values for IRI for Each Texture Type

Texture Type	No. of Sections	Minimum IRI (inches/mile)	Minimum IRI (inches/mile)	Average IRI (inches/mile)
Diamond Ground	24	24.0	128.0	68.1
Diamond Grooved	12	41.0	138.0	81.2
Longitudinally Tined	19	49.0	158.0	95.8
Burlap Drag	1	NA	NA	65.0
Longitudinally Broomed	1	NA	NA	89.0

4.3 Surface Texture Measurements

4.3.1 MPD and MTD Test Measurements

Figure 4.17 shows the MPD values measured with the LTS for the different texture types on selected sections. The results indicate that the pavement sections with diamond-grooved texture have higher MPD values than the other texture types. The lowest MPD value belonged to the longitudinally broomed texture. Of the three main textures used in California, the diamond-ground texture had lowest MPD in this small data set. A higher MPD generally correlates with greater capacity for water to move quickly out from under a tire, which would result in smaller risk of hydroplaning.

Figure 4.18 shows the MTD measured by the sand patch method, with results that generally match those from the LTS for MPD considering the conversion equation presented in Chapter 3.

4.3.2 Outflow Test Measurements

Figure 4.19 demonstrates the outflow time for different texture types. A faster outflow time indicates a greater capacity for water to escape from under a tire and a decreased risk of hydroplaning. The outflow time for diamond-grooved sections was the lowest, indicating the least risk of hydroplaning. Comparison of the outflow times with the MPD and MTD for the same sections shown before reveals that higher texture values correlate with faster outflow times, as expected.

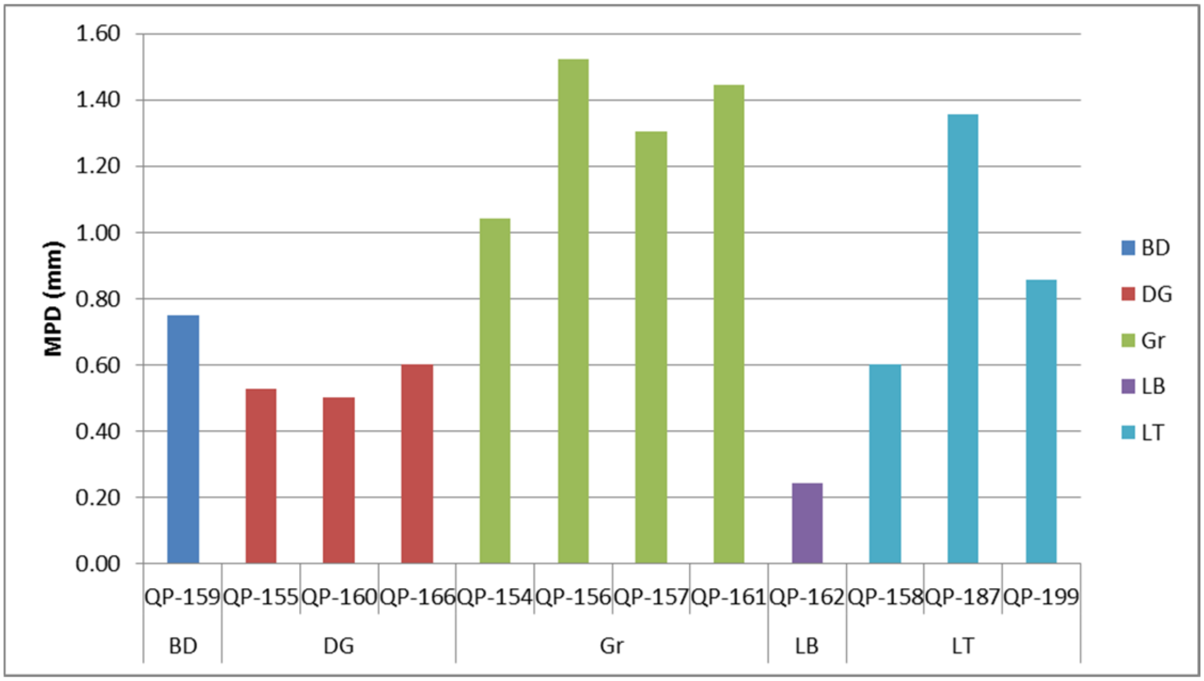

Figure 4.17: MPD values for different texture types measured by the LTS.
(Note: BD=burlap drag; DG=diamond ground, Gr=diamond grooved, LB=longitudinally broomed; LT=longitudinally tined)

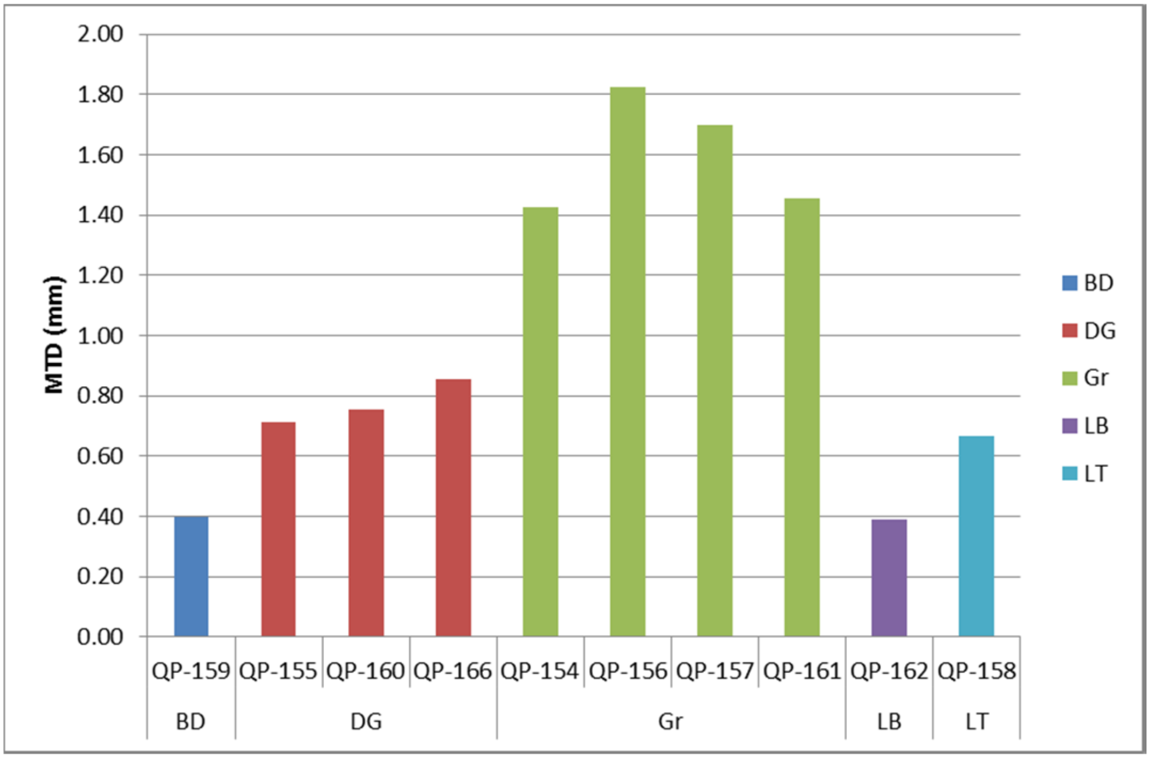

Figure 4.18: MTD values for different texture types measured by the sand patch method.
(Note: BD=burlap drag; DG=diamond ground, Gr=diamond grooved, LB=longitudinally broomed; LT=longitudinally tined)

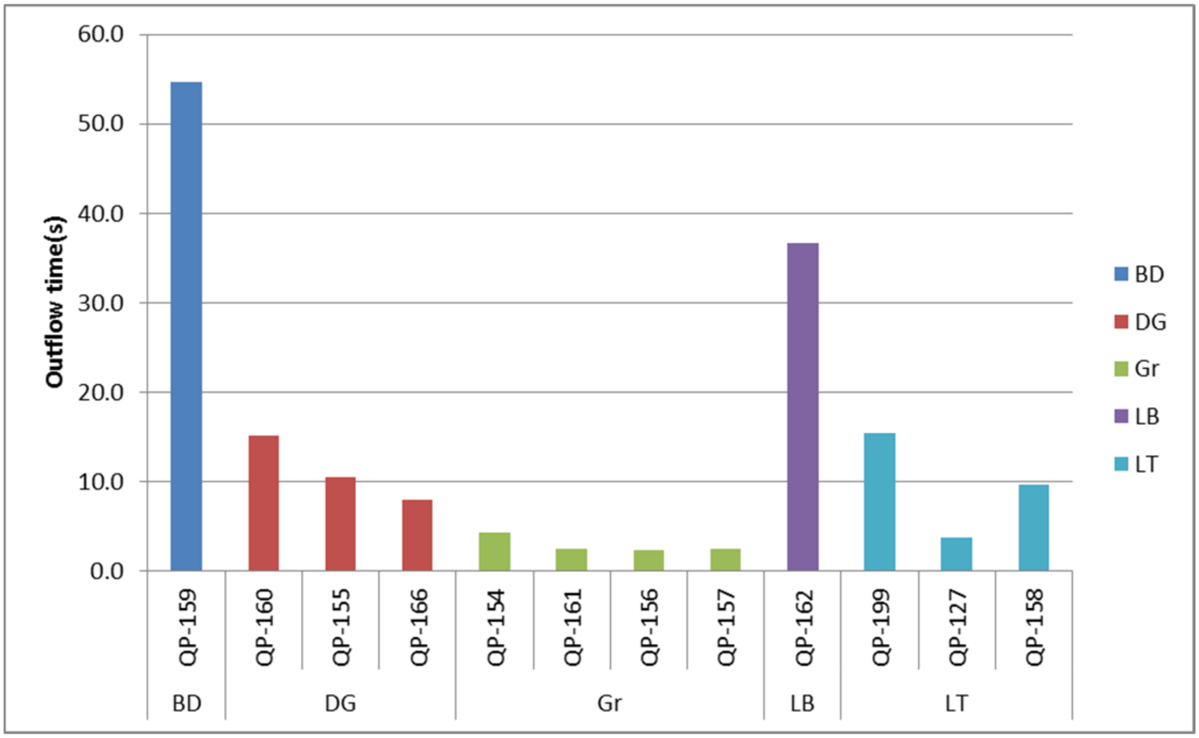

Figure 4.19: Outflow times for different texture types measured by the outflow meter. (Note: BD=burlap drag; DG=diamond ground, Gr=diamond grooved, LB=longitudinally broomed; LT=longitudinally tined)

5 ANALYSIS AND DISCUSSION OF RESULTS

Five different concrete texture types were evaluated in this study, with the primary focus on the three that are primarily used in California: diamond-ground, diamond-grooved and longitudinally tined. The study also collected information about two experimental pavement sections near Mojave on State Route 58, one with a longitudinally broomed texture and the other with a burlap-drag texture. The variability observed on the surfaces of the study sections, as well as in the measured OBSI noise levels, indicates that there is a wide range of texture conditions within each nominal surface texture type. This chapter includes the following:

- Discussion of the test results and variability for each texture type
- A comparison of overall OBSI versus time since last resurfacing
- A comparison of the three primary textures in terms of both overall OBSI and spectral content
- A comparison of the textures included in the Mojave test sections
- A comparison with another study that looked at some of the same textures commonly used in California
- A review of the trends for noise with respect to rainfall, traffic, and age
- Modeling of the effects of age, traffic, and rainfall on OBSI
- Analyses of the correlation of OBSI with various texture characterization parameters
- Analysis of the effects of joints on overall OBSI
- A comparison of OBSI on continuously reinforced concrete sections and jointed plain concrete sections with the same textures and ages
- Analysis of the IRI values for different textures and ages

5.1 Discussion of Fourth Year of Testing for Each Texture Type

The OBSI results for the three primary texture types presented in Chapter 4 indicate that the mean values for the three primary textures of interest (DG, Gr, and LT) are quite similar in the fourth year of measurements, with values of 105.5 dBA, 104.8 dBA, and 105.3 dBA, respectively. The results for the diamond-ground surfaces presented in Chapter 4 show that noise results in the fourth year of measurements span a range of about 6 dBA—with a range of only about 3 dBA for the middle 50 percent of the OBSI levels measured—for the data set, which includes measurements taken up to approximately fifteen years after the last texturing. A combination of variation in texture depth (macrotexture) and the shape of the texture (sharp, rounded, and wide versus narrow plateaus, with plateaus being the flat areas in between the grooves cut by the grinding head) is thought to be a likely reason for the variability in OBSI levels. (Figure 2.2 contains photographs of example diamond-ground surfaces.)

The results for the diamond-grooved surfaces for the fourth year of measurements span a range of about 4.5 dBA—with a range of only about 2 dBA for the middle 50 percent of the OBSI levels measured—for the data set, which includes measurements taken between five and twelve years after the last texturing. The variability is quite low for the data set of twelve sections in the fourth year of measurement. Although a combination of variation in texture depth (macrotexture) and the shape of the texture (sharp, rounded, and wide versus narrow plateaus) is thought to be a likely reason for the variability in OBSI levels, as with all the other textures, it is unclear (see the photographs in Figure 2.3) what texture characteristics are contributors to the low or high noise levels. The diamond-grooved sections are distinctive among the textures in that they had the highest MTD values and outflow times of all the types tested.

The results for the longitudinally tined sections for the fourth year of measurements span a range of about 10 dBA—with a range of only about 2 dBA for the middle 50 percent of the OBSI levels measured—for the data set, which includes measurements taken between one year and thirty-six years after the last texturing. The interquartile range reveals that the noise level of 50 percent of the sections of this texture type are expected to fall between 104.3 and 106.5 dBA, a difference of about 2 dBA, for this set of sections in which the fourth year of measurement for all but two (which were among the quietest) was within fifteen years of the last retexturing. This narrow range is unexpected given that the tining process used to create the longitudinal grooves introduces wide variations in some of the grooves' characteristics, among them differences in depth, spacing, the amount of displaced material that protrudes from the surface, and their alignment with the longitudinal direction (which is sometimes "wavy" and at other times "straight").

It is interesting to note in the photographs of longitudinally tined surfaces in Figure 2.4 that Section QP-158, which has relatively smooth surfaces on wide plateaus between the tine grooves, has a lower noise level than Section QP-101, which has narrower plateaus with rougher edges. Also, the photographs of ES-178, the noisiest longitudinally tined section, and ES-180, the quietest longitudinally tined section, provide no visual indication of why the latter section is quieter. Moreover, both have narrow plateaus and deep grooves but the difference in their overall sound intensities is about 10 dBA.

Burlap-drag sections have not been constructed on California highways for a number of years. The only burlap-drag section in the fourth year of data collection was the QP-159 experimental section in the Mojave desert that was placed specifically for comparison with other textures. This section (pictured in Figure 2.5), which was about five years old when first tested and 10 years old in the fourth year of measurement, had an average OBSI level of about 102.4 dBA over four years of measurement. The initial value measured for this section was 101.9 dBA.

From a practical point of view, longitudinal brooming can be considered equivalent to a "heavy drag" texture. The only longitudinally broomed section in the fourth year of data collection was the QP-162 experimental section in the Mojave Desert that was placed specifically for comparison with other textures. This section had an average OBSI level of about 102.4 dBA over four years of measurement. The initial value measured for this section was 103.7 dBA.

Because it was not clear from the photographs of the textures, a number of texture characterization parameters were investigated in this study in an attempt to identify the reasons for the differences in noise for the different textures and the different sections within each texture, as reported later in this chapter.

5.2 Overall OBSI Versus Years Since Last Texturing

Although there was an overall trend of increasing noise for many sections over the four years of testing—due to changes in both the pavements and potentially unaccounted for differences in testing—a plot of overall OBSI in the fourth year of measurement versus the number of years since last texturing (Figure 5.1; data in Appendix A) indicates almost no correlation between noise and years of trafficking. The plot in Figure 5.1 includes two longitudinally tined sections (QP-100 and QP-101) with ages greater than fifteen years that had relatively low noise levels, about 104 dBA. There is no apparent reason to exclude these two sections from the analysis. It can also be seen that most of the sections had OBSI levels between 103 dBA and 108 dBA, regardless of texture type.

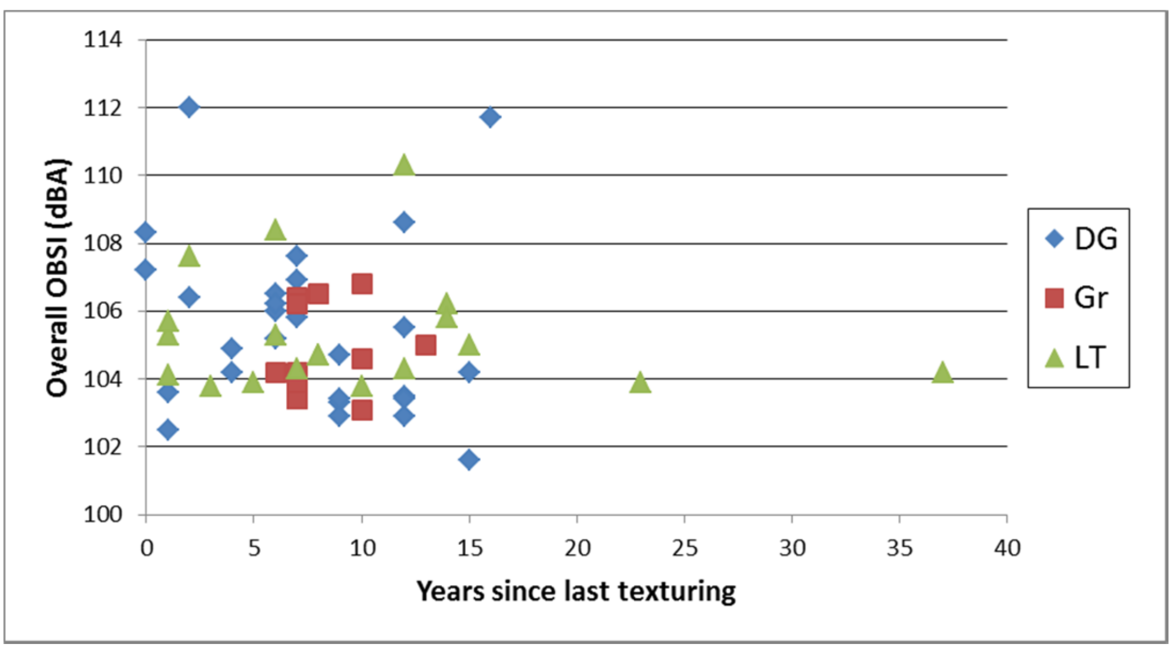

Figure 5.1: Overall OBSI in fourth year of measurement versus years since last texturing.
(Note: DG=diamond ground, Gr=diamond grooved, LT=longitudinally tined)

5.3 Comparison of Textures over Four Years of Measurement

5.3.1 Comparison of Overall OBSI

Plots of the overall OBSI measurements on the sections included in the fourth-year factorial over the four years of testing are shown in Appendix C. Table 5.1 shows the mean and the standard deviation for the overall OBSI results for each texture for the sections included in the fourth-year factorial for each year of testing, and Table 5.2 shows the mean and standard deviation of the pooled data for each texture for all four years.

In viewing Table 5.1 (and discounting the sound intensities of burlap-drag and longitudinally broomed sections since there was only one section of each), it can be seen that the means were similar for the diamond-ground, diamond-grooved, and longitudinally tined sections in each year, except for Year 2 when the longitudinally tined sections had a higher mean. It can also be seen in Table 5.1 that the standard deviations are relatively small for overall OBSI in each year, with all less than 2.5 dBA.

A look at the pooled data for the four years in Table 5.2, which includes fifty measurements on diamond-ground textures and thirty-six on diamond-grooved textures, shows that the diamond-ground and diamond-grooved textures ranked as the quietest, with a mean value of 104.3 dBA. The longitudinally tined texture was slightly noisier, with a mean of 105.4 dBA over thirty-eight measurements. These results show that the mean values for overall OBSI are very similar for all texture types, and that all of them have the same small standard deviation, about 1.9 dBA.

Figure 5.2 shows normal distribution curves for each texture type over the four years of measurements. These curves were prepared using the mean and standard deviation of OBSI levels for the combined data from Years 1, 2, 3, and 4 for each texture type shown in Table 5.2. In the figure, the diamond-ground and diamond-grooved textures have almost exactly the same distributions. Although the single Mojave experimental sections for the burlap-drag and longitudinally broomed sections were somewhat quieter than the larger populations of the three commonly used textures, general conclusions cannot be drawn from these individual sections.

Table 5.1: Mean Values of Overall OBSI Levels (dBA) by Surface Texture

Texture	Year 1					Year 2				
	N	Mean	Std. Dev.	Min.	Max.	N	Mean	Std. Dev.	Min.	Max.
DG	8	103.6	2.0	101.2	106.5	8	103.7	2.1	101.2	106.9
Gr	8	103.0	1.8	99.9	105.4	7	103.8	1.6	102.1	106.1
LT	5	103.8	0.9	102.9	105.3	5	105.5	1.3	103.6	106.7
BD	1	101.9	.	101.9	101.9	1	101.9	.	101.9	101.9
LB	1	102.5	.	102.5	102.5	1	102.5	.	102.5	102.5
Texture	**Year 3**					**Year 4**				
	N	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**N**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
DG	8	104.0	2.2	101.2	107.4	25	104.9	1.7	102.5	108.6
Gr	8	103.9	1.9	102.1	107.2	12	105.6	1.3	102.9	107.6
LT	5	105.1	1.0	103.6	106.1	19	105.9	2.3	101.6	111.7
BD	1	101.9	.	101.9	101.9	1	103.8	.	103.8	103.8
LB	1	102.5	.	102.5	102.5	1	104.2	.	104.2	104.2

Table 5.2: Mean and Standard Deviation of Sections with Different Texture Types across All Four Years

Surface Texture	Mean	Std. Dev.
DG	104.3	1.9
Gr	104.3	1.9
LT	105.4	2.0
BD	102.4	1.0
LB	102.9	0.83

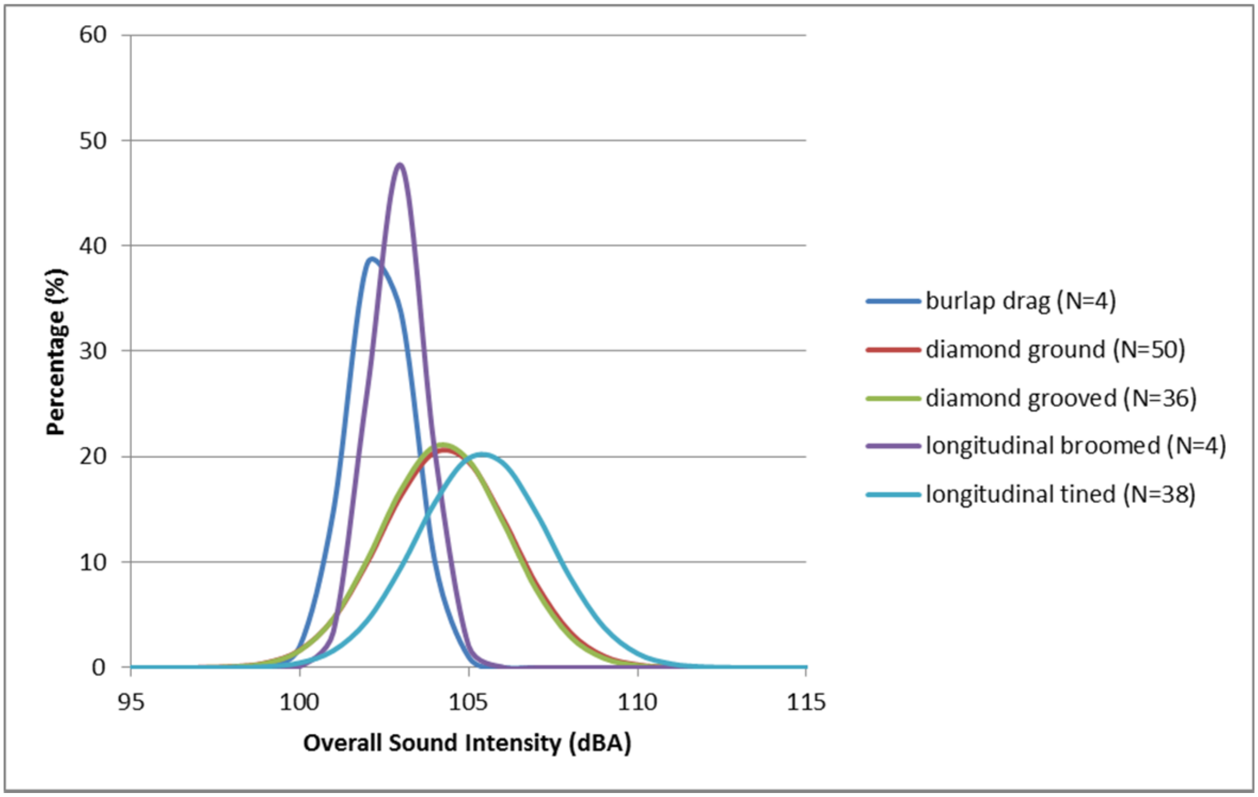

Figure 5.2: Normal distribution curves of OBSI results by texture type over four years of measurement.
(Note: BD=burlap drag; DG=diamond ground, Gr=diamond grooved, LB=longitudinally broomed; LT=longitudinally tined; numbers in parentheses indicate the total number of sections.)

Table 5.3 shows the probability that each of the paired distributions for the three primary textures of interest come from the same underlying population with the same mean using a two-tailed student *t* test and assumed unequal variances with the pooled data from all four years of OBSI measurements for each texture. The results indicate that the LT and Gr populations have the least likelihood of being from the same population. A two tailed *t*-test was conducted to test whether the means are the same for the two populations assuming different variances and having unequal sample sizes. The results indicate that the means of the DG and Gr samples are not statistically significantly different at the 95 percent confidence level and that the LT sample is statistically different from the Gr and DG samples at the same confidence interval.

Table 5.3: Statistical Comparison of Samples of Three Primary Textures of Interest

Textures	Probability that from Same Population	T Statistic	Degrees of Freedom
LT vs. Gr	0.06	2.32509	65.82711
LT vs. DG	0.44	-2.55221	67.84165
Gr vs. DG	0.33	0.00000	70.50638

5.3.2 Comparison of Spectra

Mean, maximum, and minimum OBSI for each one-third octave frequency are shown in Table 5.4. The data were averaged across all four years of measurements for the sections in the fourth-year factorial. The mean spectra for the diamond-ground (DG), diamond-grooved (Gr), and longitudinally tined (LT) textures are plotted in Figure 5.3. From the plot it can be seen that the average spectra have similar shapes. The spectra have peak OBSI values at around 800 Hz which is due in part to the A-weighting system giving greater weight to frequencies near 1,000 Hz, the frequency most important for human perception. This frequency is also typically associated with the relationship between the tread block size on the tire and the speed of tire rotation and less with the texture characteristics of the pavement surface. The 800 Hz to 1,000 Hz frequency range is typically associated with tread block noise at the 60 mph (96 km/hr) speed used for OBSI testing in this study.

The minimum and maximum OBSI spectra values for the one-third octaves are shown in Figure 5.4 and Figure 5.5, respectively. The minimum curve is the minimum OBSI value measured at each frequency from all of the sections with a given texture, and the maximum curve is the same but with the maximum value at each frequency. It can be seen in Figure 5.4 that the diamond-ground texture showed the lowest of all the minimum values for frequencies under than 1,000 Hz, while the diamond-grooved texture had the minimum value for frequencies greater than 1,000 Hz. The greater capacity of the diamond-grooved texture to allow water flow, as seen from the MPD, MTD, and outflow meter data, likely indicates that it is also the best at allowing air to flow from under the tire, which is the primary noise mechanism for frequencies above 1,000 Hz. The lower macrotexture of the diamond-ground texture is likely the reason that it had the lowest low frequency noise levels. The longitudinally tined texture exhibited the highest minimum values among all the texture types at frequencies for most of the spectrum.

Figure 5.5 shows that the longitudinally tined texture had the highest maximums for frequencies of 2,000 Hz and lower, indicating that high macrotexture is the likely cause. At higher frequencies the diamond-grooved texture generally had lower maximum noise and the diamond-ground and longitudinally tined textures were similar.

Table 5.4: Sound Intensity in One-Third Octaves of Sections over Four Years of Data Collection

Texture	Stat.	400	500	630	800	1,000	1,250	1,600	2,000	2,500	3,150	4,000	5,000	Overall
DG (N=49)	Min.	81.4	80.9	86.1	94.8	96.4	94.2	92.1	89.8	86.2	81.6	79.1	76.3	101.2
	Avg.	86.3	88.1	92.6	98.6	98.4	95.9	95.2	93	89.6	84.8	80.9	78.7	104.3
	Max	90.5	94.3	98.5	103.1	102.1	99.8	99.5	97.5	96.5	90.5	83.8	81.7	108.6
Gr (N=36)	Min.	82.5	83.4	87.4	95.2	94.8	93.1	90.2	88.4	84.3	80.7	77.1	74.3	99.9
	Avg.	85.9	87.9	93.2	99.6	98.6	96.5	95.2	93.7	90	86.9	82.6	79	104.3
	Max	89.2	92.8	98.1	102	101.4	99.9	98.1	96.3	94.6	92.4	86.5	82.3	107.6
LT (N=34)	Min.	84.5	85.5	89.1	94.2	96.6	93.7	92.4	89.9	84.8	80.4	78.7	74.8	101.6
	Avg.	87.3	89.3	93.8	99.7	99.3	96.6	96.4	94.3	90.8	86.3	81.3	78.9	105.4
	Max	94.4	97.4	104	107.3	104.1	101.1	100	98.1	97.1	91.6	84.8	81.7	111.7
BD (N=4)	Min.	83	82.2	86.2	94.7	96.9	93.2	95.6	94.8	91	87.1	81.1	81.5	101.9
	Avg.	84.8	84.1	88.3	96.2	97.7	93.7	96.3	95.2	91.9	88.1	83.8	81.6	102.4
	Max	86.3	85.3	90.5	96.9	98.2	94.5	97	95.9	93.5	90.2	85.1	81.8	103.8
LB (N=4)	Min.	84.3	83.5	87.6	95.7	96.9	93.8	96.5	95.3	91.4	88.1	81.6	81.9	102.5
	Avg.	85.5	85.5	89.5	96.7	97.8	94.3	97.1	95.9	92.7	89.1	84.5	82.8	102.9
	Max	86.9	86.6	91	97.7	98.4	95.2	97.6	96.5	94.6	92.1	86.2	83.5	104.2

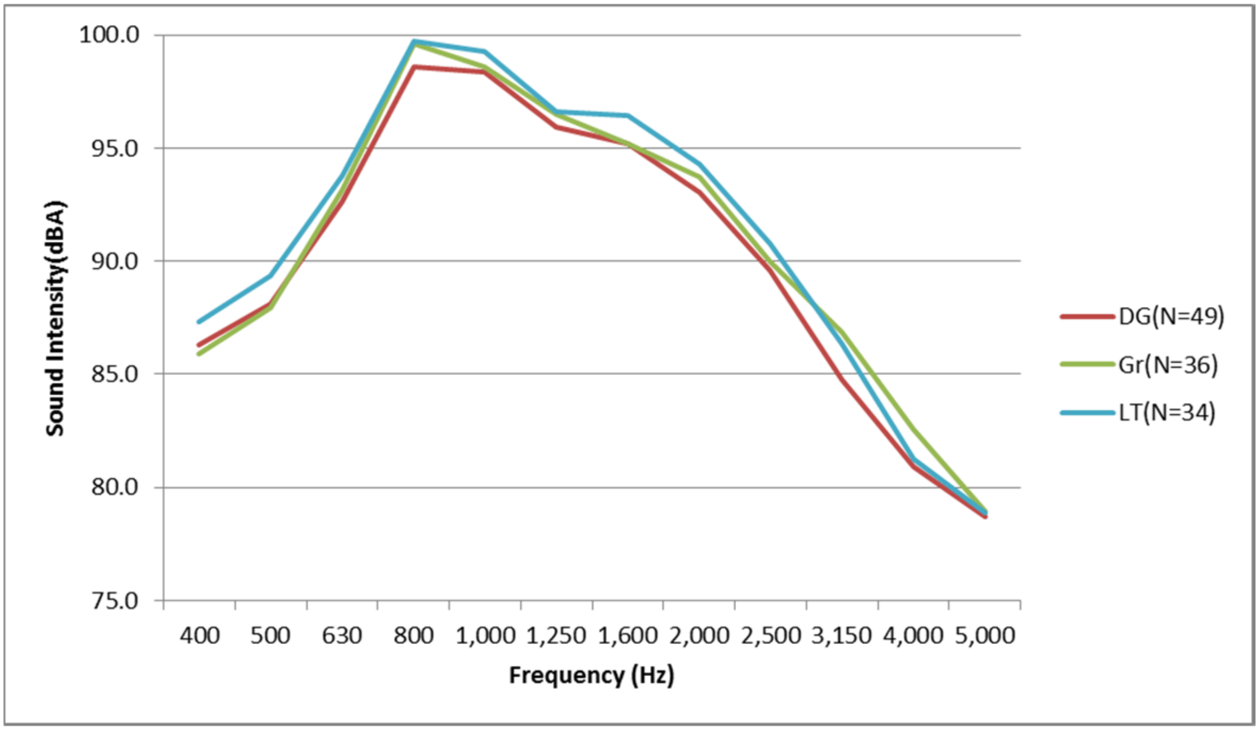

Figure 5.3: Comparison of average OBSI spectral content.
(Note: DG=diamond ground, Gr=diamond grooved, LT=longitudinally tined; numbers in parentheses indicate the total number of sections.)

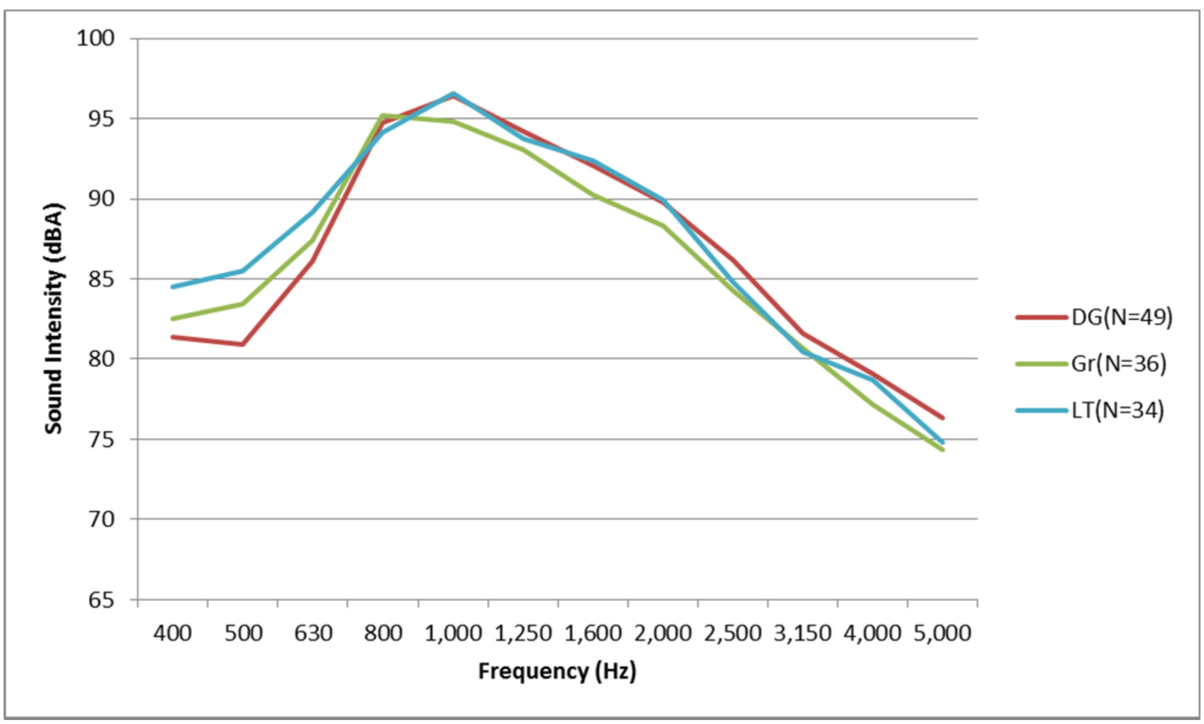

Figure 5.4: Comparison of minimum OBSI spectral content.
(Note: BD=burlap drag; DG=diamond ground, Gr=diamond grooved, LB=longitudinally broomed; LT=longitudinally tined; numbers in parentheses indicate the total number of sections.)

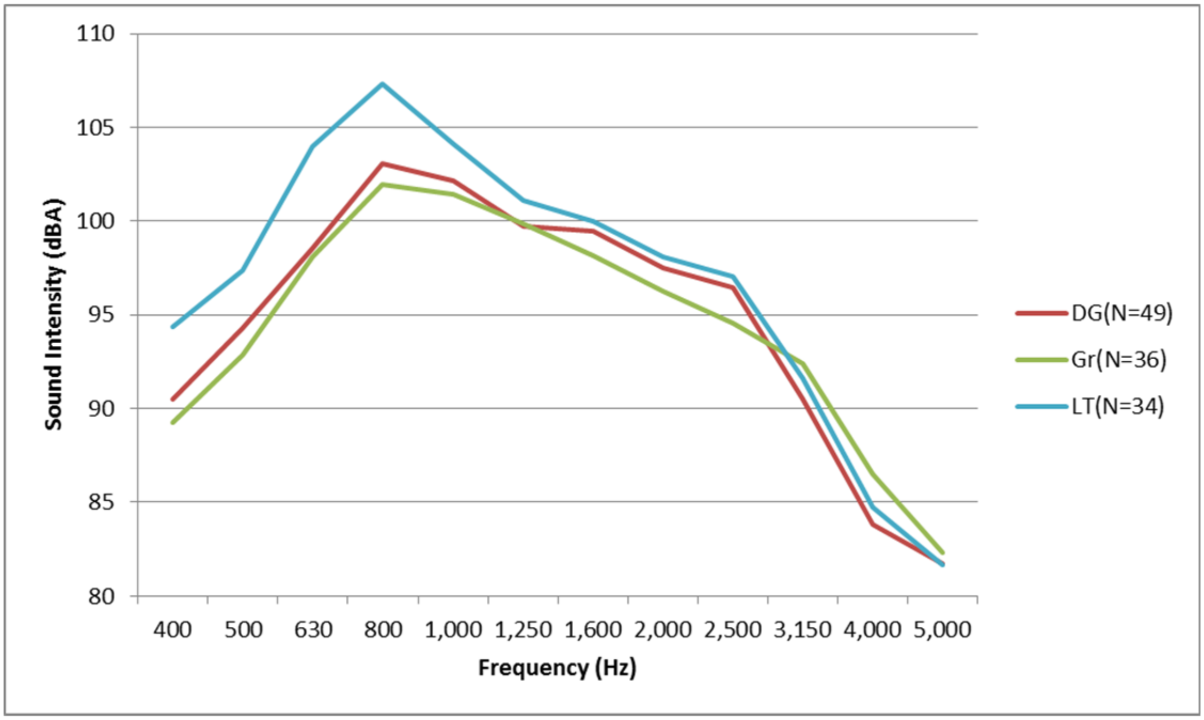

Figure 5.5: Comparison of maximum OBSI spectral content.
(Note: BD=burlap drag; DG=diamond ground, Gr=diamond grooved, LB=longitudinally broomed; LT=longitudinally tined; numbers in parentheses indicate the total number of sections.)

5.4 Comparison of Mojave Experimental Sections

The results of four years of testing on the Mojave test sections, which were built in 2005 and last textured in 2006, are shown in Figure 5.6 in terms of overall OBSI (data for this plot is included in Appendix A). Over the four years of the study, the average values were 102.8 dBA for the burlap-drag section, 103.7 dBA for the three diamond-ground sections, 103.9 dBA for the four diamond-grooved sections, and 103.7 dBA for the longitudinally broomed section. From these results it can be seen that on average the overall OBSI was similar for all the textures, although there was a range of almost 5 dBA between the quietest and the noisiest in the fourth-year results. In the fourth year, the diamond-ground sections were generally noisier than the diamond-grooved sections, the opposite of the first three years of measurement.

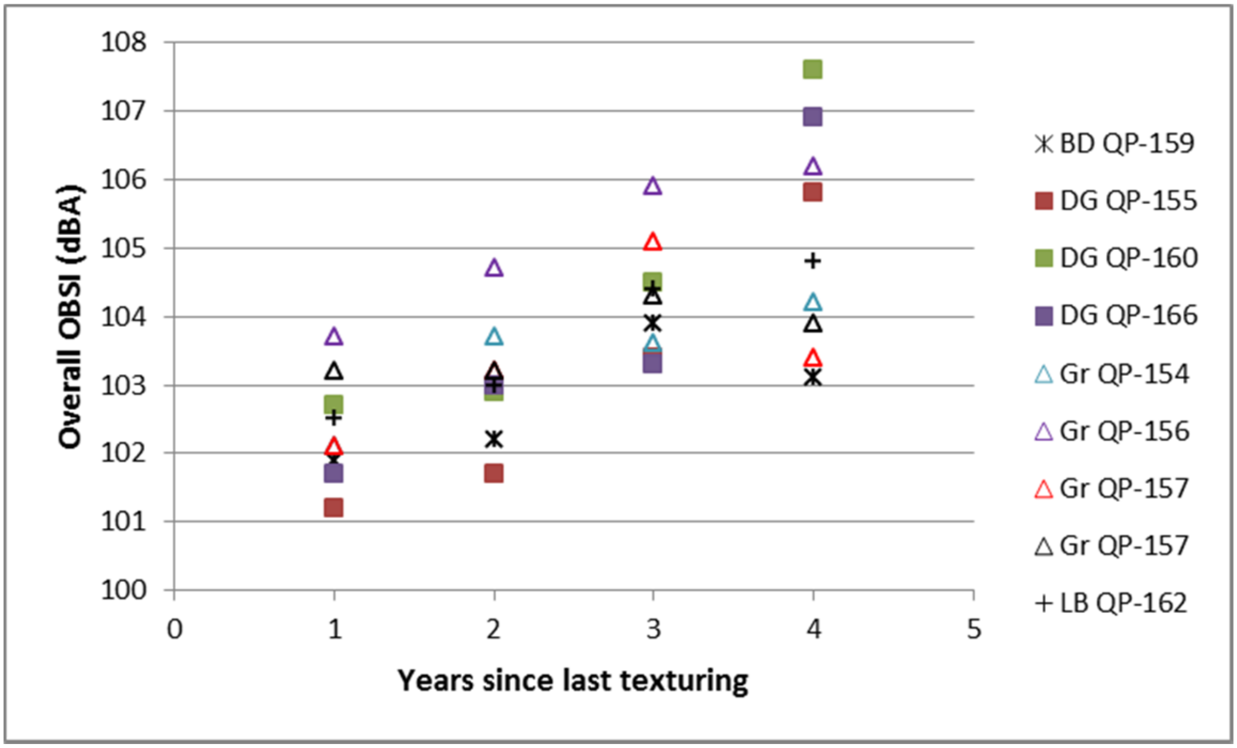

Figure 5.6: Overall OBSI for four years of testing on Mojave test sections.
(Note: BD=burlap drag; DG=diamond ground, Gr=diamond grooved, LB=longitudinally broomed)

5.5 Comparison with Other Research Studies

A report in 2008 by the National Concrete Pavement Technology Center (NCPTC) (*9*), which compiled tire/pavement noise data measured with the OBSI method from several locations around the United States, indicated that diamond-ground pavements offer low levels of tire pavement noise. The study ranked four texture types as follows: (1) diamond ground, (2) burlap drag, (3) longitudinal tining, and (4) transverse tining. The NCPTC report did not include diamond-grooved or longitudinally broomed concrete pavement sections.

Later, the equipment used in the NCPTC study was modified and the tires were changed to SRTT, with the results shown in Figure 5.7 *(10)*. The results with the SRTT have higher OBSI values for the different textures than the previous study. However, comparison with the results of the study presented in this report, summarized in Figure 5.8 for the three primary textures used in California, indicates that while the ranking between the diamond-ground and longitudinally tined sections is the same for the two studies, the California study shows OBSI results that are higher than those in the NCPTC study.

Another research study was conducted by the National Cooperative Highway Research Program (NCHRP) in 2009 *(11)*. The NCHRP study measured the noise levels of different texture types in the following states: Alabama, California, Colorado, Florida, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, North Carolina, North Dakota, Pennsylvania, Texas, and Wisconsin. It can be seen in Table 5.5 that the measured noise levels in the NCHRP study and this research study are very close.

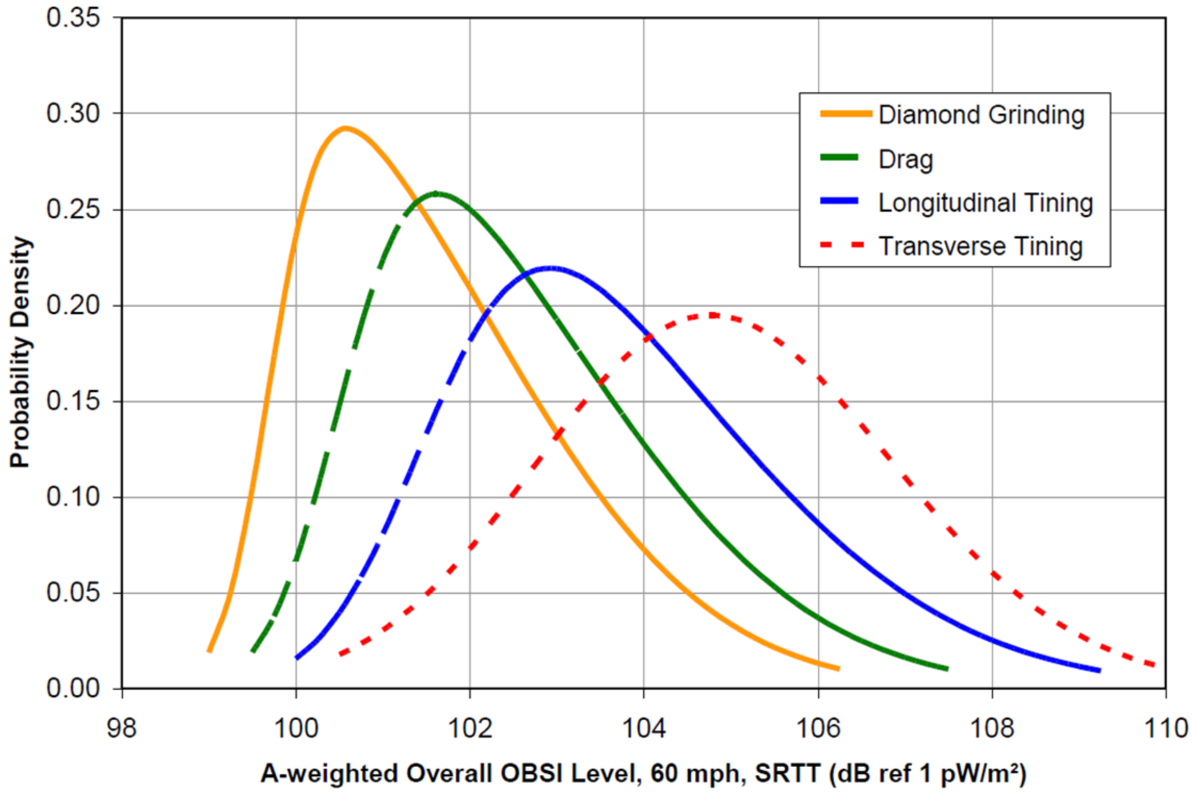

Figure 5.7: Probability distributions of OBSI noise levels for concrete pavement textures as reported by the National Concrete Pavement Technology Center in 2010 (*10*).

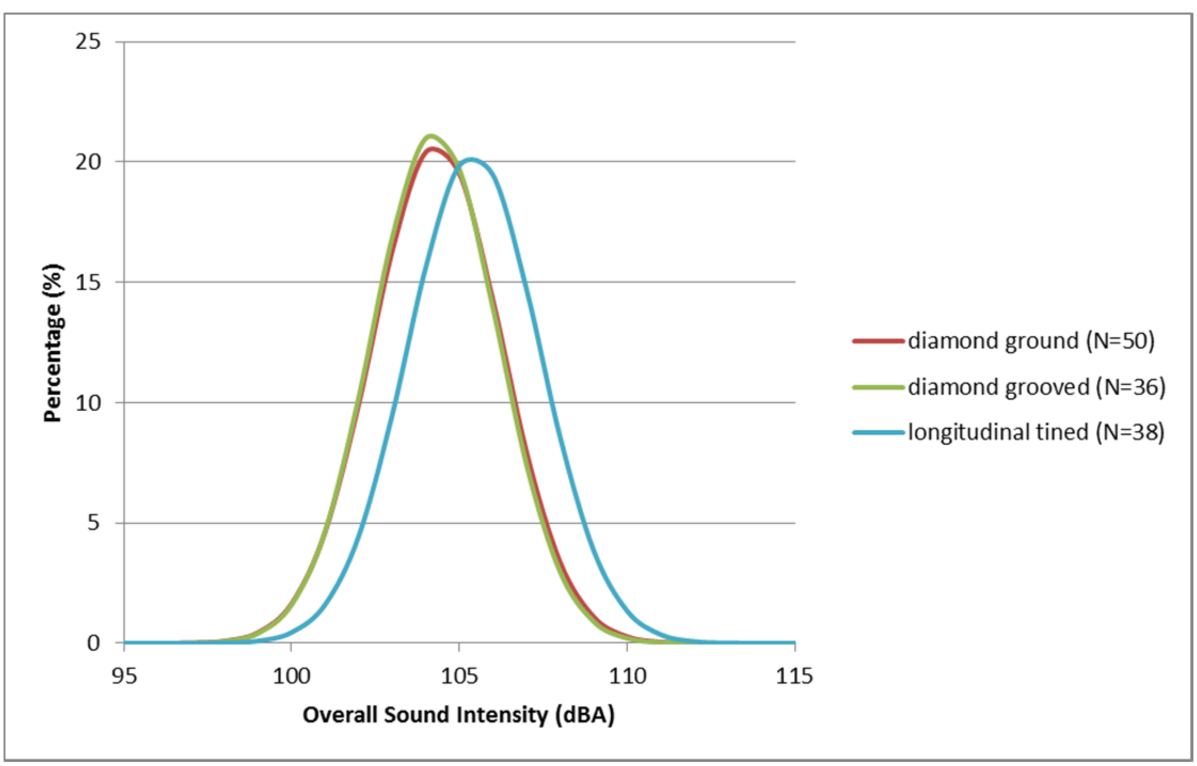

Figure 5.8: Distributions of OBSI noise levels over four years of measurement. (Note: numbers in parentheses indicate the total number of sections.)

Table 5.5: Sound Intensities for Different Texture Types in this Study Compared to NCHRP Study

Texture Type	Sound Intensity in NCHRP Study *(10)*	Sound Intensity in This Study (all four years)
1. Diamond ground	105.1	104.3
2. Diamond grooved	105.2	104.3
3. Longitudinally tined	105.3	105.4

5.6 Effects of Roughness, Traffic, Rainfall, and Texture Age

In order to study the effects of traffic, rainfall, and texture age, traffic and precipitation data for all test sections were extracted from Caltrans databases. Figure 5.9 shows the effect of pavement age on overall sound intensity for the high and low traffic categories as defined in Section 2.2. The difference between the overall sound intensity of the pavement sections with high and low traffic volumes diminishes as the texture ages. The figure also shows noise-versus-age categories of less than 2 years, 2 to 10 years, 10 to 12 years, and 20 to 40 years, which were selected for the figure based on the demographics of the sections. There is a fairly wide range of overall OBSI in each age category for both traffic categories.

The effect of pavement age and traffic category was investigated for each individual texture type, although the sample sizes were small. Figure 5.10, Figure 5.11, and Figure 5.12 show the overall sound intensity for diamond-ground, diamond-grooved, and longitudinally tined sections, respectively. For each texture type, the overall sound intensity of the sections with high traffic volume was generally a little higher than that for sections with low traffic volume. The overall sound intensity generally increased as the pavements aged, however there does not appear to be a strong correlation with time for the sections included in the study, as could also be seen in Figure 5.1. The increase of sound intensity with pavement age might be due to pavement distresses other than texture abrasion, such as cracking.

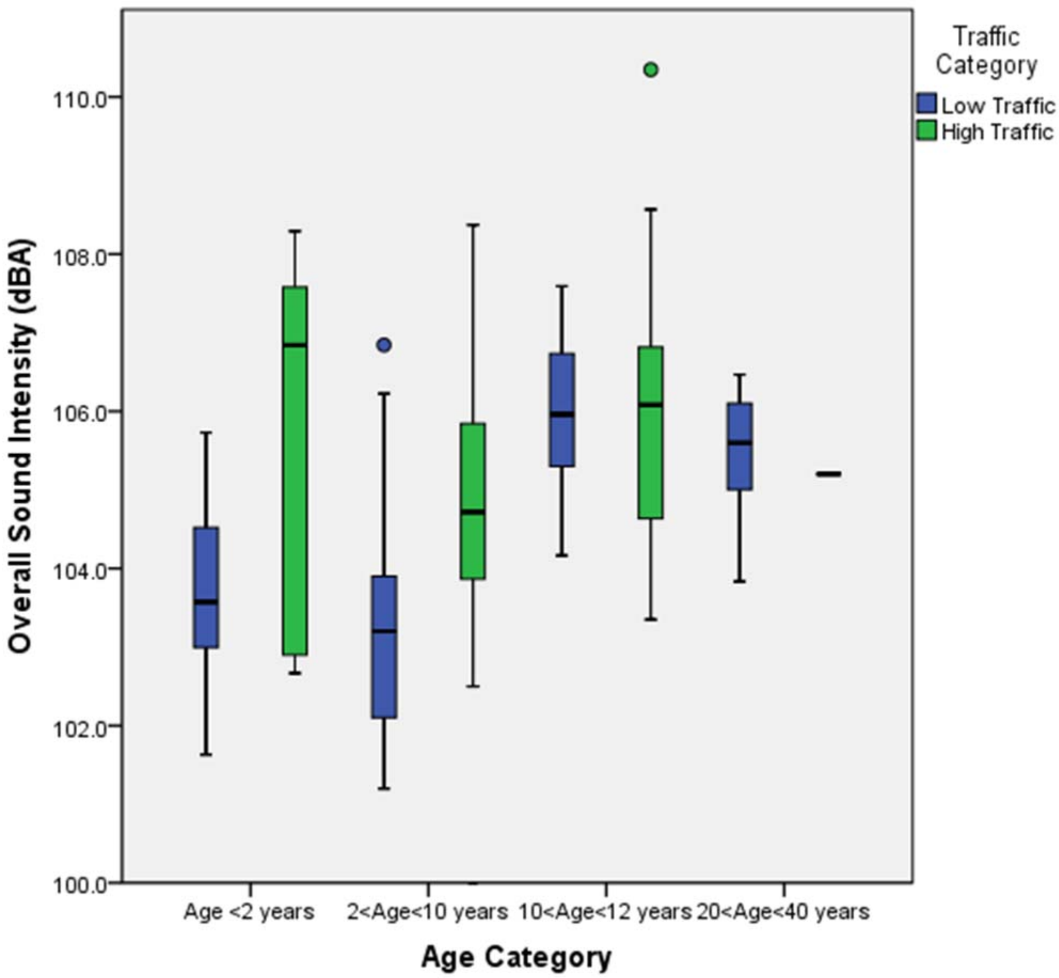

Figure 5.9: Effect of texture age and traffic category on the overall sound intensity for all sections.

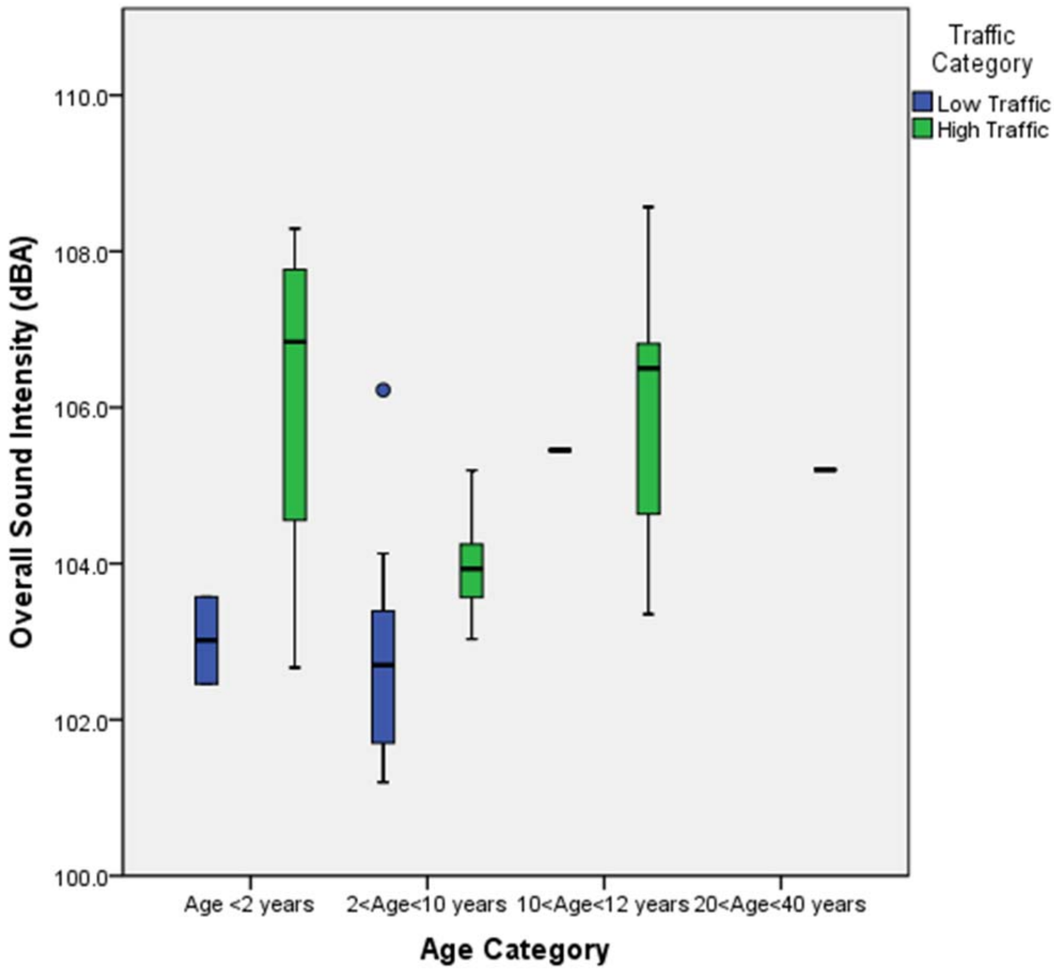

Figure 5.10: Effect of texture age and traffic category on the overall sound intensity for diamond-ground sections.

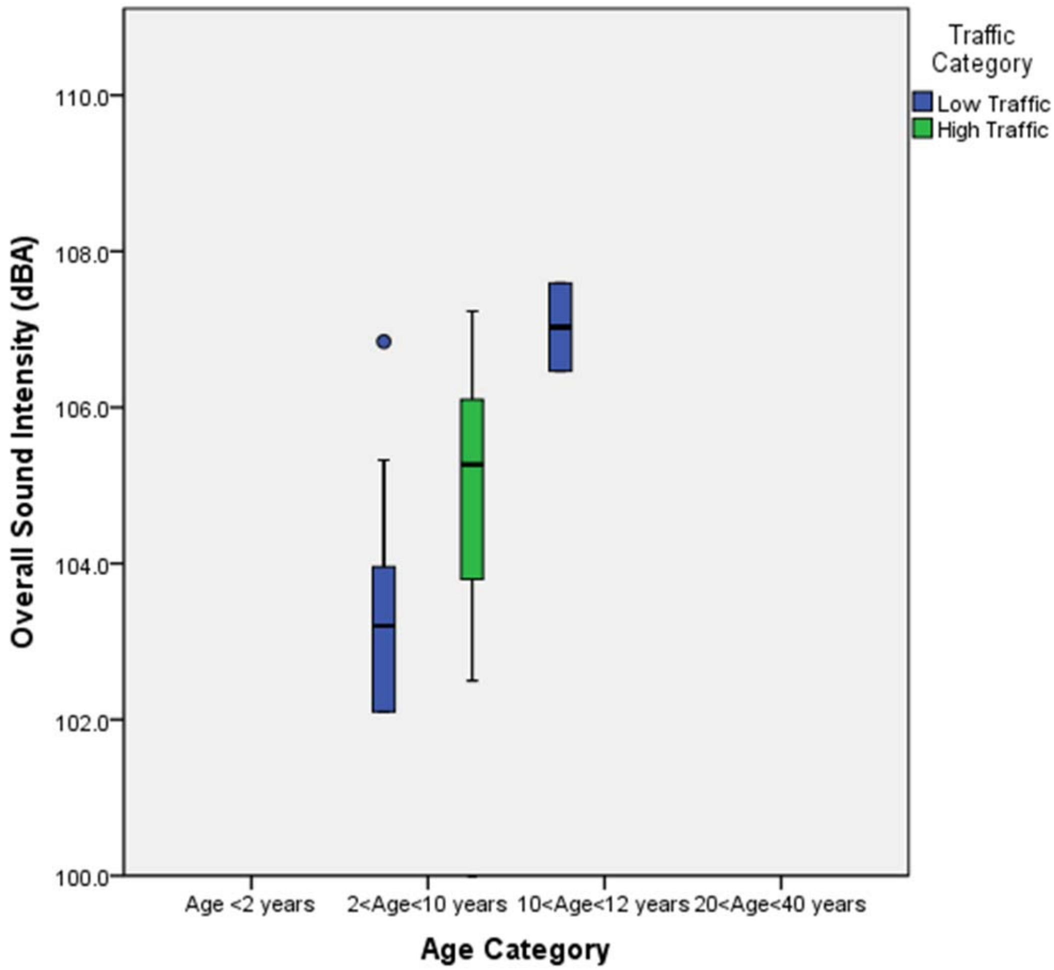

Figure 5.11: Effect of texture age and traffic category on the overall sound intensity for diamond-grooved sections.

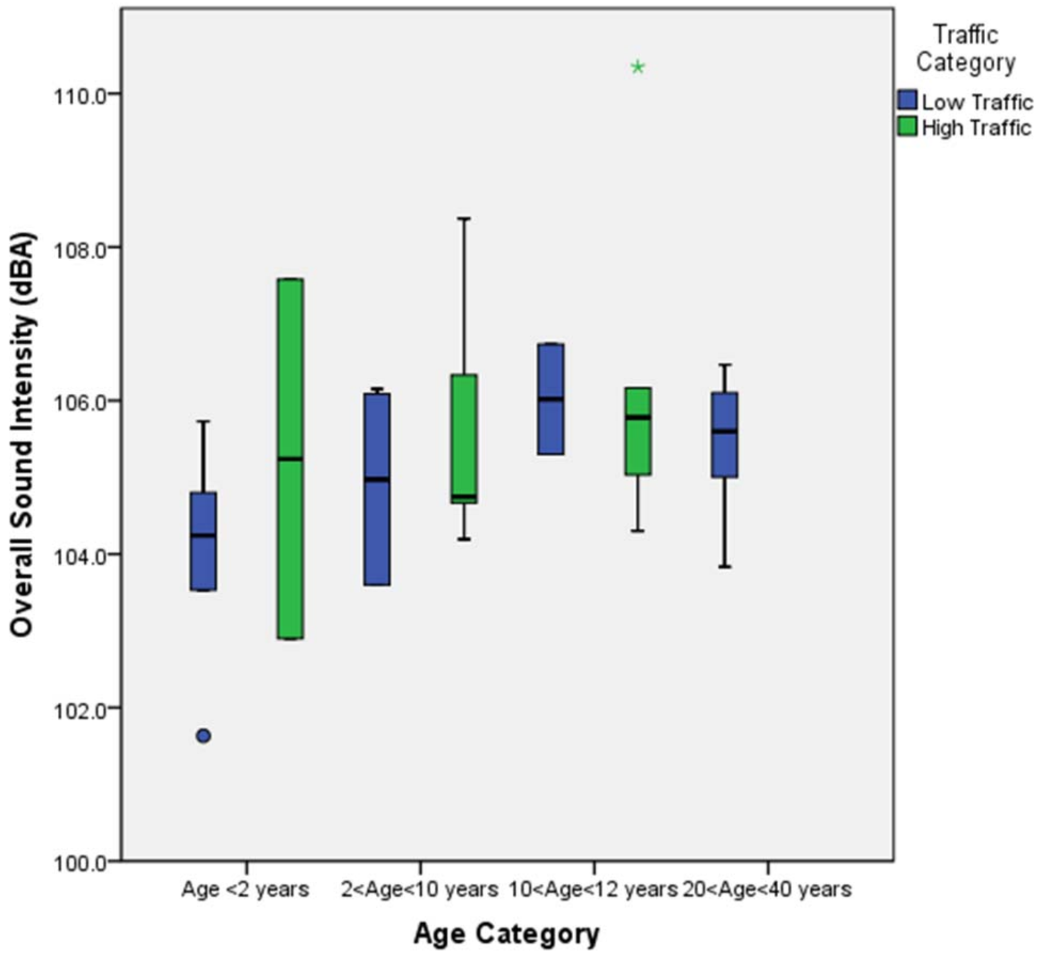

Figure 5.12: Effect of texture age and traffic category on the overall sound intensity for longitudinally tined sections.

5.7 Modeling of Effects of Traffic and Rainfall

Figure 5.13 shows scatter plots of overall OBSI versus AADT/lane (total traffic), AADTT/lane (truck traffic), annual rainfall, and texture age. From the first row of plots where OBSI is the dependent variable it can be seen there is a trend of increasing OBSI with both increasing AADT and increasing AADTT, and that there is a tremendous amount of scatter. The same can also be seen for overall OBSI and rainfall. In all of these cases, the trend is as expected, with increasing traffic and rainfall damaging the surface and increasing positive texture. The trend that can be seen for overall OBSI and texture age is also as expected, with increasing noise as the surface is exposed to traffic and rainfall. Again, there is a tremendous amount of scatter in the plot. The plots showing the relationships between the traffic and rainfall variables indicate that they are generally uncorrelated. The traffic and environment variables shown here are per year, rather than cumulative over time, and should therefore be independent of age provided there is no correlation unintentionally built into the factorial from selection of the section locations.

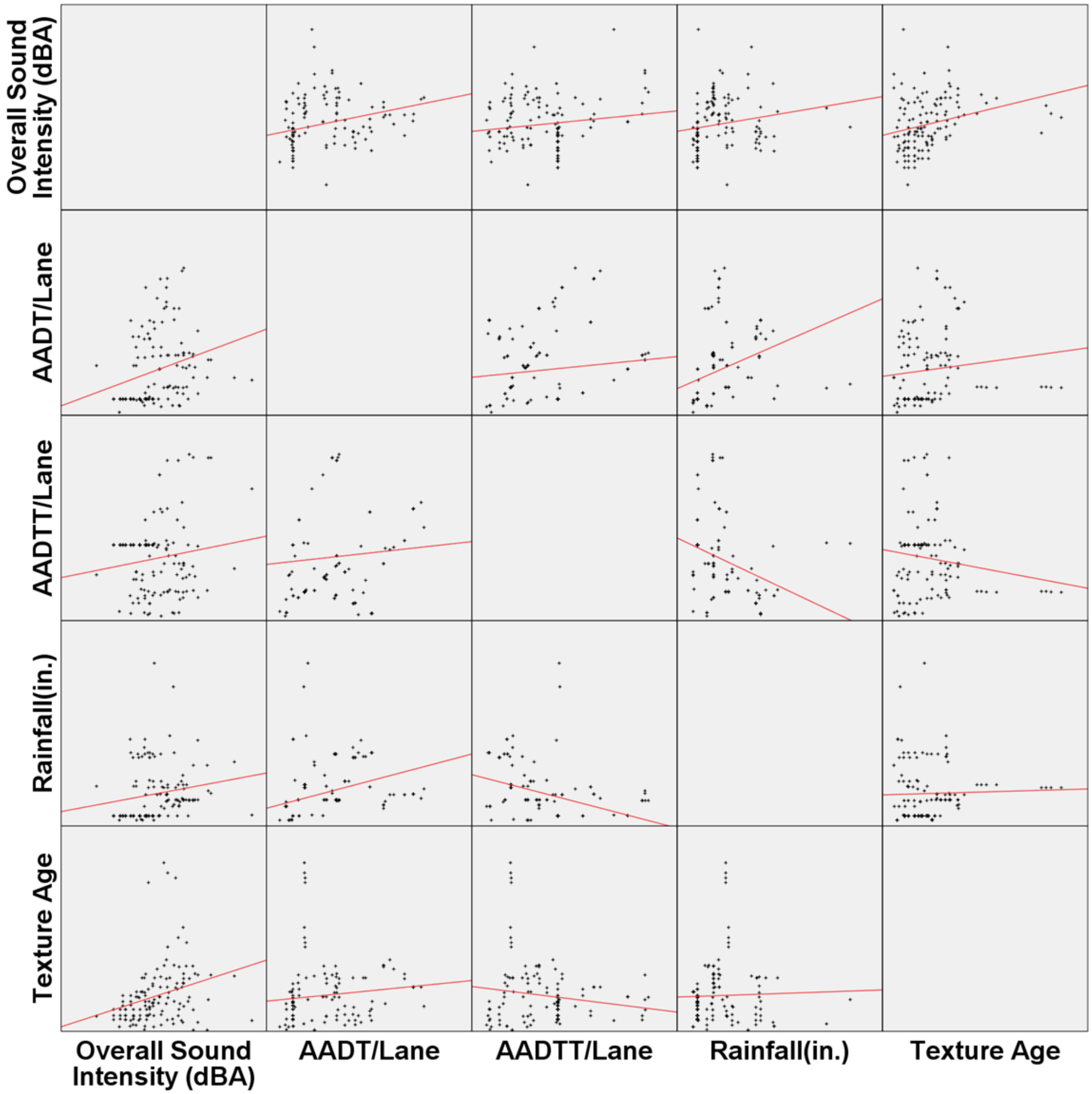

Figure 5.13: Scatter plots of overall OBSI versus traffic, rainfall, and age.

Statistical analyses and multi-variate linear regression analysis were used in order to quantify the effect of each variable shown in Figure 5.13 on the overall sound intensity. The analyses and modeling were conducted using the data for all of the sections included in the fourth-year factorial and considering all the measurements on those sections over the four years.

The detailed results of the statistical analyses are shown in Appendix D. Those results are summarized here. As mentioned previously, in order to simplify the effect of traffic and rainfall on the overall sound intensity of pavement sections, two levels were defined for each variable. Traffic was categorized as *high* if the AADT (two-way) was greater than 32,000 vehicles per day, with smaller amounts categorized as *low*. Rainfall was based on annual average rainfall in California from 1960 to 1990, with amounts greater than 620 mm (24.4 inches) categorized as *high* and smaller quantities as *low*. These levels of traffic and rainfall were also used for the modeling of asphalt pavement noise in a companion study.

The first analyses evaluated the interactions of traffic, rainfall, and age using the GLM Univariate. The results indicated that the traffic category, rainfall, and texture age were not correlated in the pooled data set. Analysis of a model only using the traffic and rainfall categories, with all the texture types pooled together, indicated that texture age has a significant effect on overall sound intensity at the 95 percent confidence interval, while the rainfall and traffic categories did not meet that threshold of significance.

A model that did not include texture type was then developed with covariates of texture age, and continuous variables of annual rainfall, average annual daily traffic per lane (AADT/Lane), and average annual daily truck traffic per lane (AADTT/Lane) as additional explanatory variables. The ANOVA indicated that the whole model is significant at the 0.05 significance level and that AADTT/Lane, rainfall, and texture age seem to have coefficients that are significant at the 0.95 level in explaining the variation of the overall sound intensity. AADT/Lane was not significant.

Another model was developed with overall sound intensity as the dependent variable, texture type as the categorical variable, and AADT/Lane, AADTT/Lane, rainfall, and texture age as the covariates. All interaction between the covariates and the texture type were first included in the model, and then the insignificant interaction terms were removed for the final model. The results indicate that of the covariates, texture type, rainfall, average annual daily truck traffic, and texture age are significant factors affecting the overall sound intensity. Among all the interactions, it was evident that texture type and texture age have a significant interaction, while the interactions of texture type with the other covariates are not significant. However, the adjusted R^2 was only 0.308, indicating that the model does not explain much of the differences in overall OBSI in the data set.

Finally, individual models were developed for each texture type. Since there were not many pavement sections with the burlap-drag and longitudinally broomed texture types, the analysis was performed only for the diamond-ground, diamond-grooved, and longitudinally tined texture types, the prevalent ones used in California.

Results of that modeling indicate the following:

- The linear model with the explanatory variables of rainfall, texture age, AADT/Lane, and AADTT/Lane is very poor in explaining overall OBSI for the diamond-ground and longitudinally tined textures, with adjusted R^2 of 0.149 and 0.010, respectively. For the diamond-grooved texture, the model is better able to explain overall OBSI, as indicated by an adjusted R^2 of 0.573.
- Texture age, rainfall, and AADTT/Lane are significant factors at the 95 percent confidence level, affecting the overall sound intensity of the diamond-grooved texture, and the model predicts an increase in overall OBSI with an increase in texture age, rainfall, and AADTT/lane, as expected. For the model for the diamond-ground texture, the only significant variable is texture age, and for the longitudinally tined texture model there are no significant variables at the 95 percent confidence level.

5.8 Effects of Surface Texture Characterization

It was clear from the statistical modeling that considered the texture type, texture age, rainfall, and traffic variables that overall OBSI must primarily be controlled by the characteristics of the surface texture on the individual sections. This idea was examined further by looking at the correlation of overall OBSI with a number of road surface texture characterization parameters. To elucidate the effects of texture shape on different elements of the tire/pavement noise mechanism, the correlation of the surface parameters with the one-third octave band noise levels was also explored.

Figure 5.14 shows an example of a patch of pavement texture obtained from the LTS that was further analyzed in order to calculate the statistical parameters. Similar profiles from other test sections were used to develop road surface characterization parameters for the analyses. The results of that investigation are included in Appendix E and plots of the correlation with each parameter with OBSI are shown in Appendix F.

The results indicate that there is a strong relationship between overall sound intensity and skewness, standard error of $\tan\beta_0$, and standard error of R_t. The magnitude of overall sound intensity increases with an increase in the absolute value of skewness, standard error of $\tan\beta_0$, and standard error of R_t. No strong relationship was found between the overall sound intensity and macrotexture parameters such as MPD, MTD, and outflow time.

In order to study what component of the noise is more affected by these texture parameters, the correlation coefficients for the relationship between one-third octave band frequencies and the above texture parameters were calculated and are shown in Appendix E.

The results shown in Appendices E and F indicate that the texture parameters that had a strong relationship with overall sound intensity, i.e., skewness, standard error of $\tan\beta_0$, and standard error of R_t (see Appendix D for definitions) also had a strong correlation with noise levels for frequencies less than 1,600 Hz, as did MPD and MTD. High frequency noise correlated best with the outflow meter test results. This makes sense, since high frequency noise is primarily associated with the ability of air to escape from under the tire.

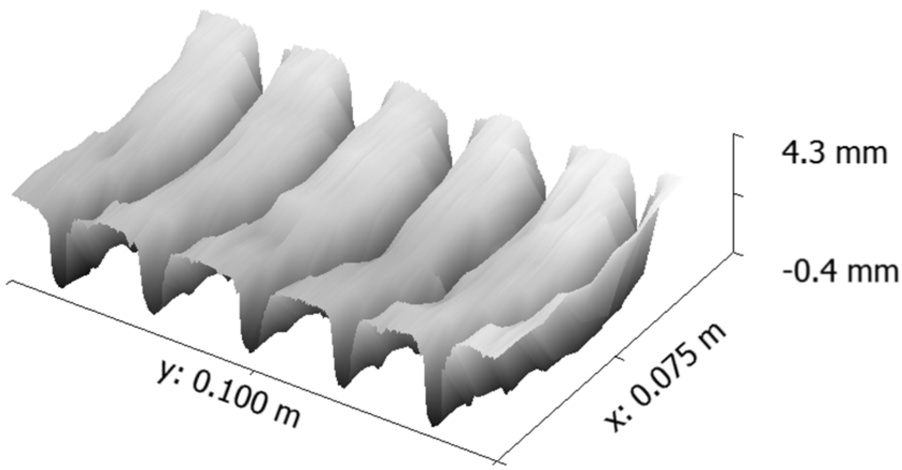

Figure 5.14 Example of a pavement texture for analysis (QP-154).

5.9 Effects of Joints on Tire/Pavement Noise

In addition to the effects of pavement texture, the measured OBSI levels presented in this report include the effects of joint slap, faulting, and sealant overbanding. Each of these additional factors, if they are present, would increase the OBSI level above that caused by the texture alone. Joint slap is primarily a function of the empty cross-sectional area of a joint below the surface acting as an amplifier for the sound of a tire passing over the joint. Faulting causes noise as a tire passes over a fault. Joint sealant that is present above the surface of the joint (referred to as *overbanded* sealant*)* creates a positive texture that results in noise from tire vibration.

Some preliminary data indicating the added effects of joint faulting, joint opening cross-sectional area, and joint sealant recess depth on the overall OBSI for concrete pavement surfaces have been recently developed by Purdue University and the American Concrete Pavement Association using the Purdue Tire Pavement Test Apparatus in the laboratory with some field validation at the MnROAD test track in Minnesota *(7)*.

Donavan has developed a method for estimating the effect of joint slap based on the cross-sectional area of a joint opening. This method is based on a theoretical acoustical model validated with field measurements. The model considers the unsealed cross-sectional area (depth and width) of a joint below the surface of the pavement, which amplifies the sound of a tire passing across the joint, but it does not consider faulting or overbanded sealant (*8*). In the fourth year of data collection for this study, the width, depth, and fault values were measured for all the joints in the section.

Figure 5.15 and Figure 5.16 show the distribution of joint depth and width, respectively, across all the test sections where measurements were taken, with the results summarized in Table 5.6. About 80 percent of the joints had a depth less than 0.6 inches (16 mm). There were, however, joints with depths up to 2.5 inches (64 mm). Joint width varied in the range of 0.2 to 0.8 inches (5 to 20 mm) for almost all measured joints. No faulting was observed on the majority of the sections, as shown in Figure 5.17.

Figure 5.18 shows the calculated values of joint noise based on Donavan's method. The joint noise can go up to 5 dBA, but for about 85 percent of the joints the calculated joint noise was less than 0.6 dBA. Table 5.6 shows the joint measurements and the calculated joint noise for all the test sections. Except for one section, QP-187 where the joint noise was about 2 dBA due to very deep joints, the overall effect of joint noise was less than 1 dBA for all sections and could be safely assumed to be negligible.

Table 5.6: Joint Measurement Results and Calculated Joint Noise for Different Textures

Texture	Section	Average Depth (in.)	Average Width (in.)	Average Fault (in.)	OBSI (dBA)	Average Calculated Joint Noise (dBA)
BD	QP-159	0.4	0.6	0.0	103.8	0.4
DG	QP-155	0.5	0.5	0.0	103.1	0.4
	QP-160	0.3	0.6	0.0	104.1	0.2
	QP-166	0.5	0.5	0.0	103.9	0.4
Gr	QP-154	0.4	0.5	0.0	104.2	0.3
	QP-156	1.1	0.5	0.0	106.8	0.9
	QP-157	0.4	0.5	0.0	104.6	0.1
	QP-161	0.3	0.5	0.0	105.3	0.1
LB	QP-162	0.4	0.5	0.0	104.2	0.2
LT	QP-127	0.5	0.3	0.0	105.8	0.1
	QP-158	0.4	0.5	0.0	106.0	0.1
	QP-187	2.3	0.3	0.0	104.3	2.0
	QP-199	0.1	0.6	0.0	104.3	0.0

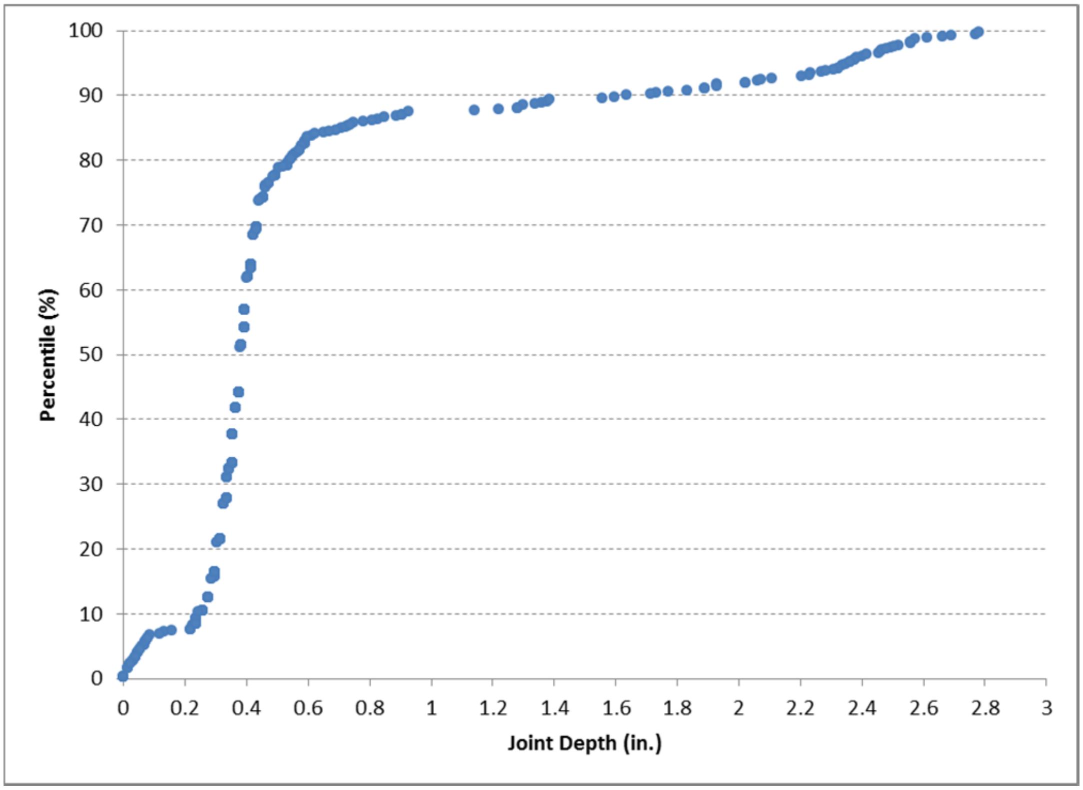

Figure 5.15: Distribution of joint depth across all sections.

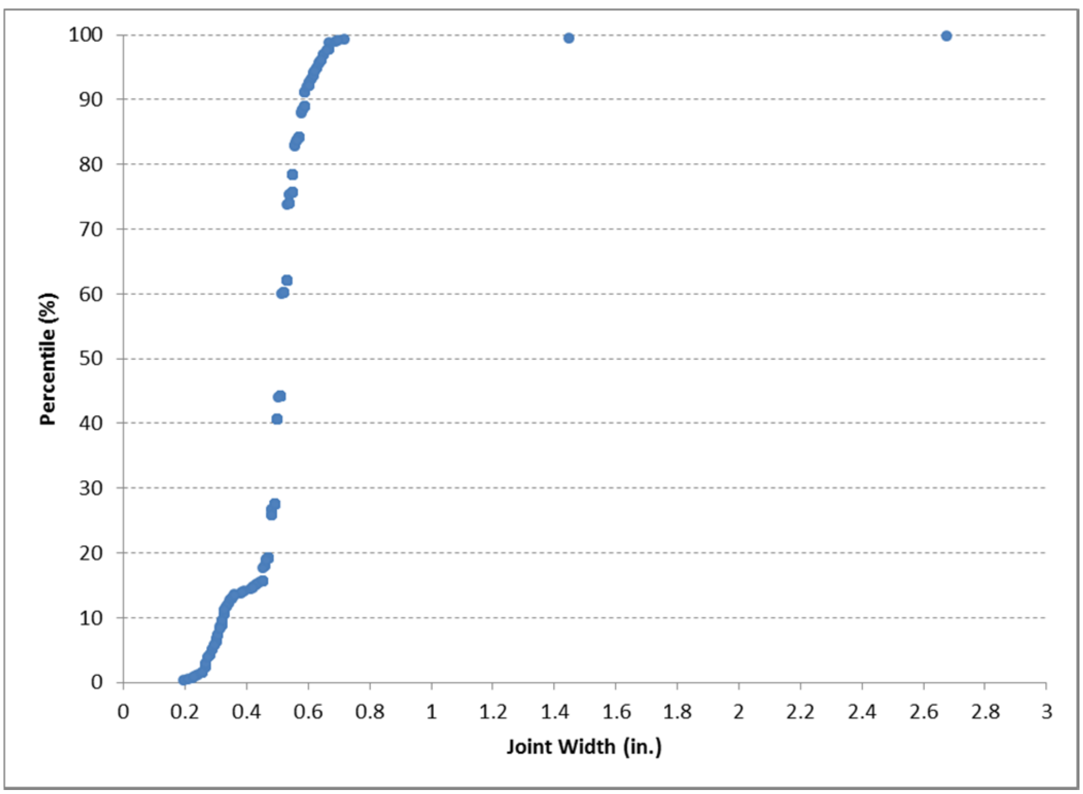

Figure 5.16: Distribution of joint width across all sections.

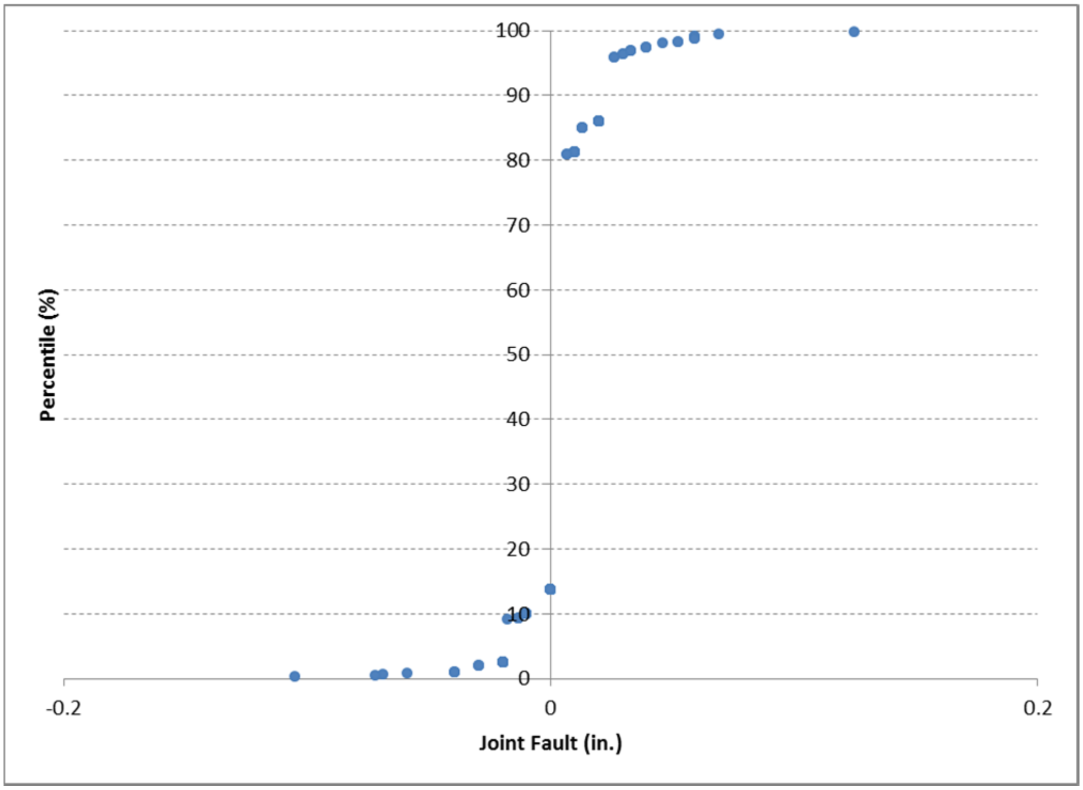

Figure 5.17: Distribution of joint faulting across all sections.

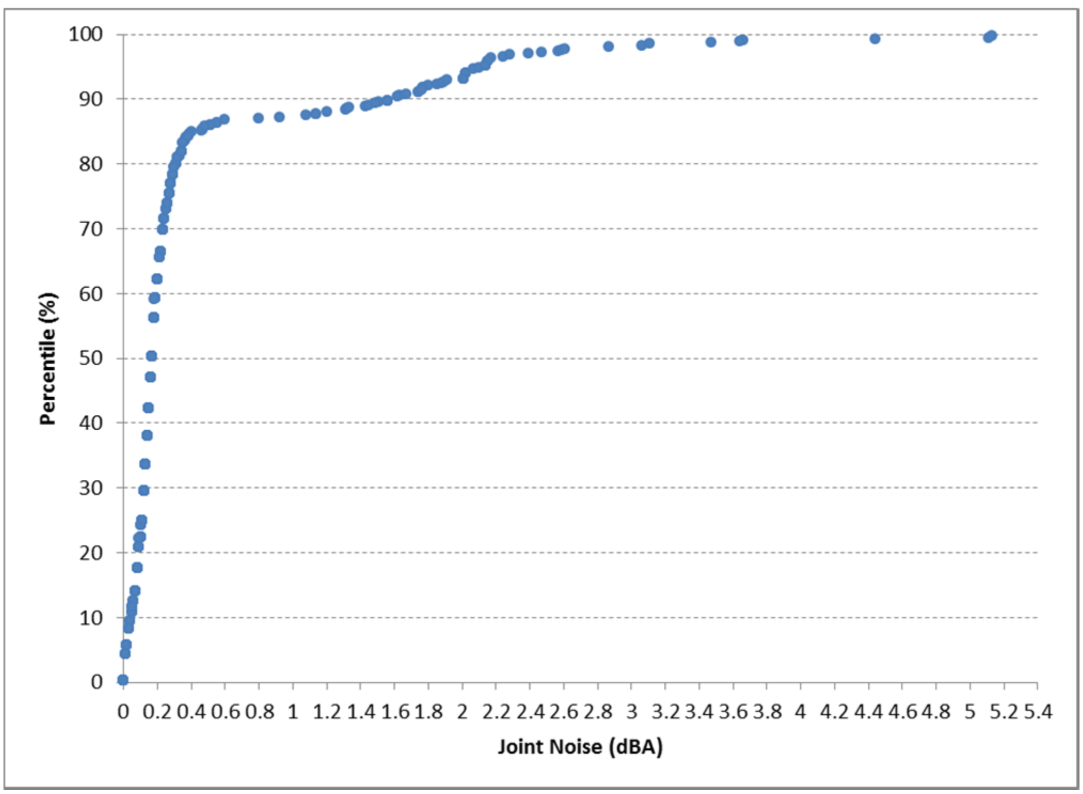

Figure 5.18: Distribution of calculated joint noise across all sections.

5.10 Comparison of OBSI on CRCP and JPCP

Continuously reinforced concrete pavement (CRCP) and jointed plain concrete pavement (JPCP) sections of similar ages were selected for a comparison of OBSI results. Table 5.7 shows the selected sections, which include one JPCP section and one CRCP section with diamond-ground textures, and four CRCP sections and three JPCP sections with longitudinally tined textures. The table also shows the overall OBSI values and the OBSI values for each frequency band. The sections all had less than six years of traffic since their last resurfacing at the time of OBSI measurement.

As can be seen in Figure 5.19, the overall OBSI values are similar for the two types of pavement. The average overall OBSI value for the CRCP sections was 105.4 dBA and the average value for the JPCP sections was 106.1 dBA. This slight difference might be attributable in part to the joints on the JPCP sections contributing to the noise, however, as was noted in the previous section of this report, the contribution of joint noise would be expected to be less than 1 dBA for most JPCP pavements. It should also be noted that this is a small sample and is insufficient for further statistical analysis.

Figure 5.20, Figure 5.21, and Figure 5.22 show plots of the OBSI spectra data for the DG textures for JPCP and CRCP, for the JPCP with LT textures, and for the CRCP with LT textures, respectively. The results indicate that the overall shape of the frequency plot may be different for the JPCP and the CRCP sections, with all four JPCP sections showing a characteristic bump in noise at the 1,600 Hz frequency, while only one of the five CRCP sections (QP-203) exhibits this shape. One of the CRCP sections (ES-178), which has a longitudinally tined texture and was less than four years old at the time of testing, had much higher noise than the rest of the JPCP and CRCP sections, with an overall OBSI of 111.7 dBA, the second highest noise level measured in the fourth year. This section has higher OBSI levels in particular at frequencies of 1,600 Hz and lower indicating high macrotexture.

Table 5.7: Sections Selected for Comparison of CRCP and JPCP Noise

Section	Texture	Type	Climate Region	Traffic	Rainfall	Surfacing Date	Overall OBSI (dBA)	OBSI (dBA) at 1/3-Octave Frequency Band (Hz)											
								400	500	630	800	1,000	1,250	1,600	2,000	2,500	3,150	4,000	5,000
ES-177	DG	CRCP	High Desert	Low	Low	Sep 26, 2007	103.9	86.95	89.7	94.3	97.7	97.6	96.6	93.3	90.2	86.2	82.2	79.1	76.5
QP-207	DG	JPCP	Inland Valley	Low	Low	Dec 3, 2007	106.2	87.4	90.0	95.8	100.6	99.5	97.3	97.1	94.7	91.3	87.4	80.5	80.5
ES-178	LT	CRCP	Inland Valley	High	Low	Aug 23, 2010	111.7	94.4	97.4	104.0	107.3	103.9	101.1	99.3	96.5	93.5	91.6	80.9	80.0
QP-201	LT	JPCP	Inland Valley	High	Low	Dec 7, 2011	107.6	88.8	92.3	97.5	101.0	101.3	98.4	98.3	96.5	94.7	86.6	79.9	78.7
ES-180	LT	CRCP	Desert	Low	Low	Jan 1, 2012	101.6	85.6	86.9	89.2	94.2	96.6	94.0	92.4	89.9	84.8	80.4	78.7	74.8
QP-129	LT	JPCP	Inland Valley	Low	Low	Jul 1, 2008	106.2	87.3	88.8	95.8	100.5	98.8	96.7	97.9	96.1	92.2	89.8	81.0	80.6
ES-181	LT	CRCP	Desert	Low	Low	Jan 2, 2012	104.2	88.6	90.2	93.8	97.9	98.5	95.8	94.2	91.3	87.3	82.7	79.2	75.9
QP-203	LT	CRCP	High Mountain	Low	High	Apr 1, 2012	105.7	85.6	89.6	94.4	99.4	99.3	96.4	97.7	95.5	92.2	86.6	79.9	78.5
QP-199	LT	JPCP	High Mountain	Low	High	Nov 22, 2006	104.3	84.5	87.9	92.0	97.9	98.0	94.6	96.8	94.5	90.9	86.5	80.2	79.0

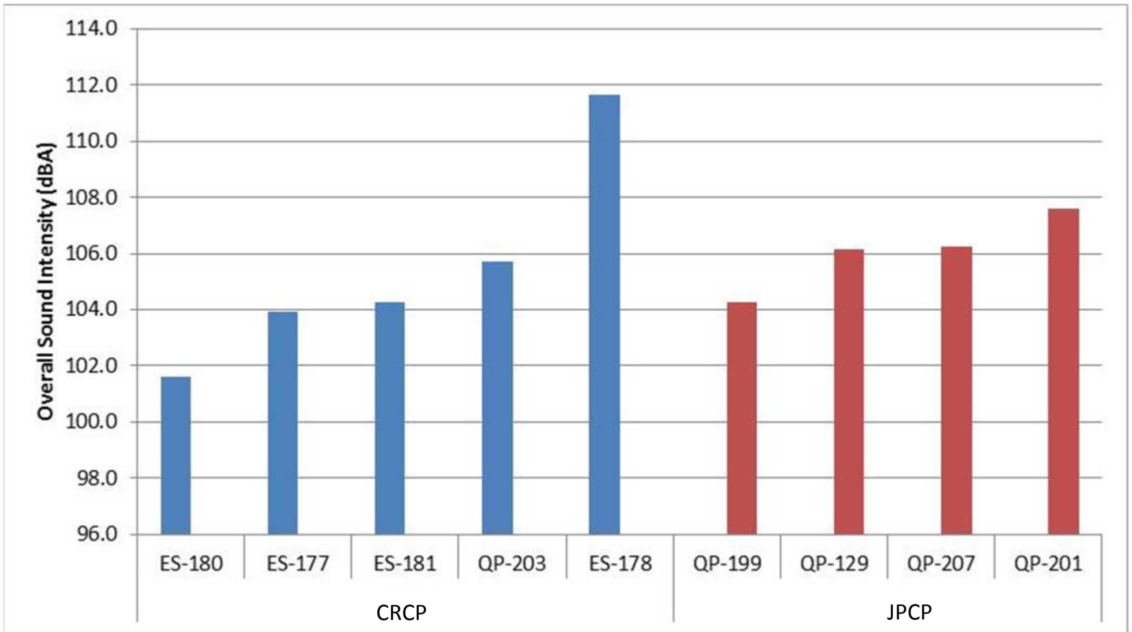

Figure 5.19: Comparison of overall OBSI levels for CRCP and JPCP comparison.

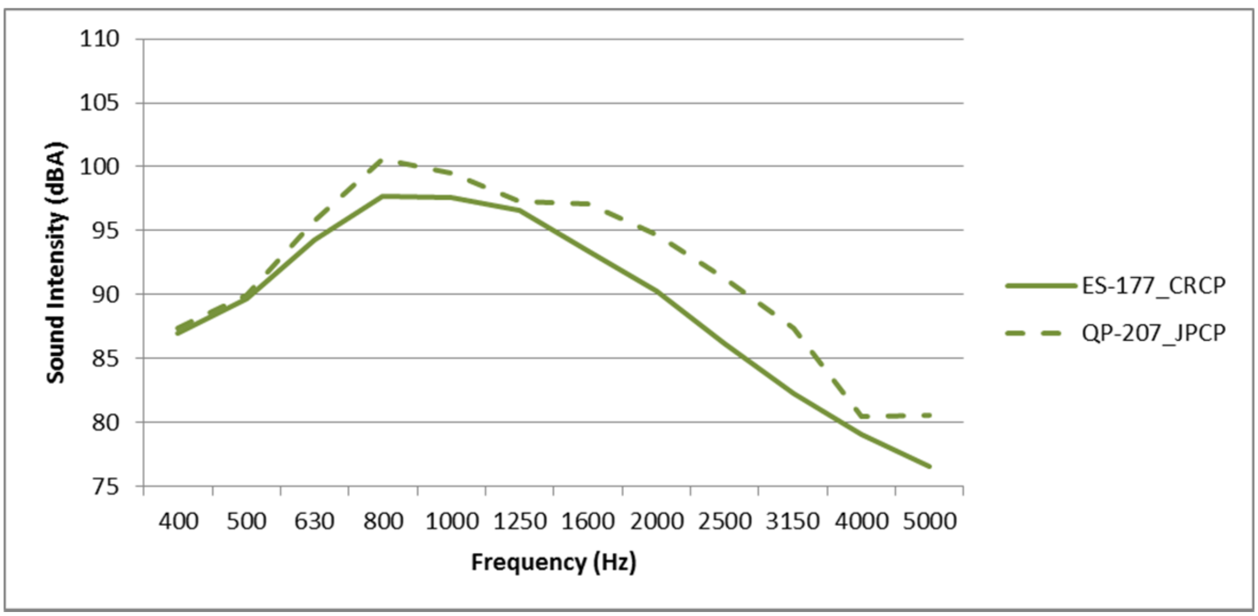

Figure 5.20: Comparison of OBSI frequency spectra for CRCP and JPCP sections with DG texture.

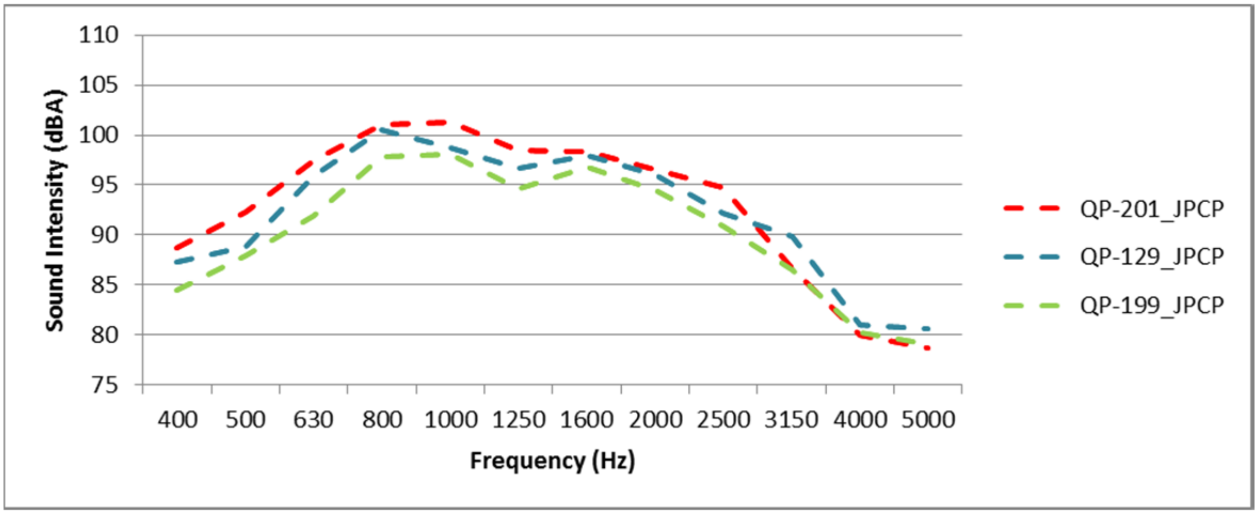

Figure 5.21: Comparison of OBSI frequency spectra for JPCP sections with LT texture.

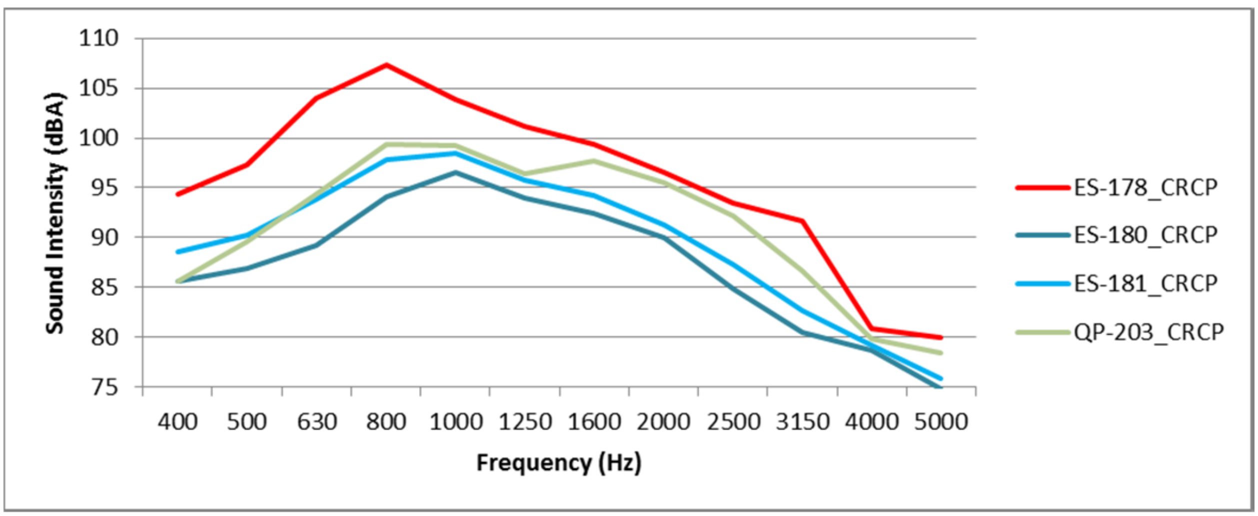

Figure 5.22: Comparison of OBSI frequency spectra for CRCP sections with LT texture.

5.11 Analysis of IRI for Different Textures and Correlation with OBSI

5.11.1 IRI for Different Textures

The measurements of IRI from the fourth year, shown in Table 2.1, are summarized in Figure 5.23 and Table 5.8. In Figure 5.23 it can be seen that the age distribution for the three textures considered, diamond-ground, diamond-grooved, and longitudinally tined, are similar except for two older longitudinally tined sections. The results also indicate that there is little or no trend for IRI versus age for the sections included in this study, which had ages less than fifteen years since last retexturing. It can generally be assumed that construction of each of these textures would involve smoothing the existing pavement as part of creating the texture, which indicates that the range of IRI values shown is primarily a function of construction technique and potentially also of the roughness of the pavement prior to texturing. Most of the test sections had IRI values less than 140 inches/mile (2.25 m/km) and many had values less than about 60 inches/mile (approximately 1 m/km), which is considered smooth. For reference, the IRI value that warrants treatment, following the decision trees in the Caltrans pavement management system, is 170 inches/mile (2.73 m/km).

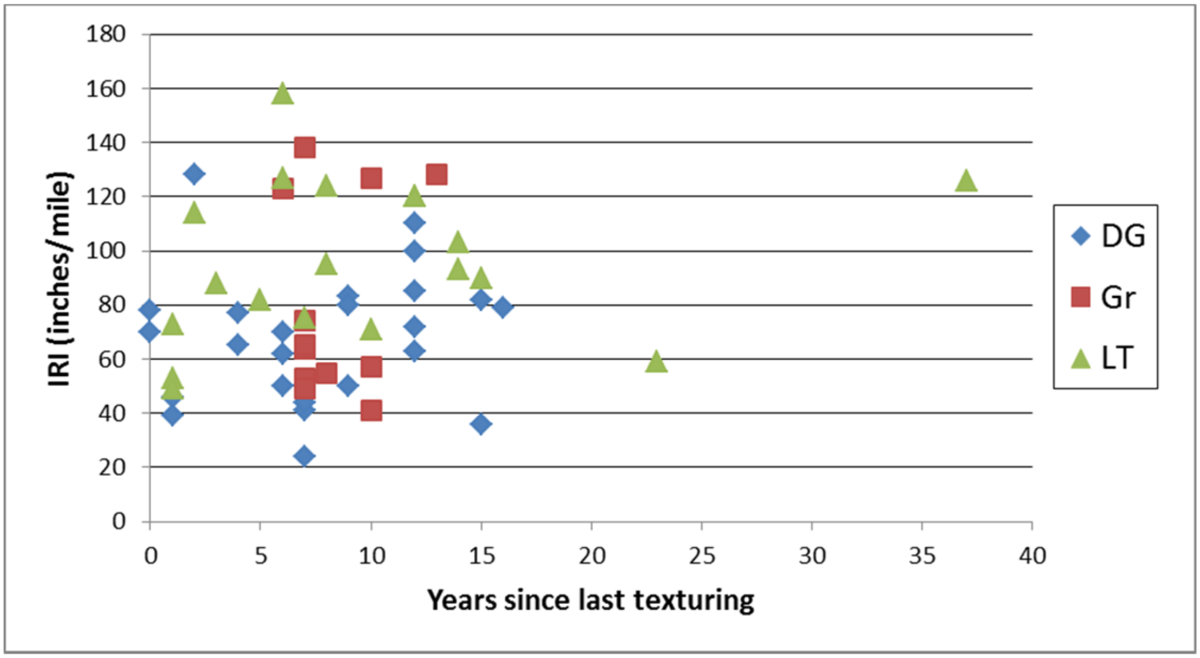

Figure 5.23: IRI versus age for different texture types.
(DG=diamond ground, Gr=diamond grooved, LT=longitudinally tined)

Table 5.8: Summary Statistics for IRI Measurements by Texture

Texture Type	No. of Sections	Minimum IRI (inches/mile)	Maximum IRI (inches/mile)	Average IRI (inches/mile)
Diamond Ground	24	24.0	128.0	68.1
Diamond Grooved	12	41.0	138.0	81.2
Longitudinally Tined	19	49.0	158.0	95.8
Burlap Drag	1	NA	NA	65.0
Longitudinally Broomed	1	NA	NA	89.0

5.11.2 Correlation of IRI and OBSI

Figure 5.24 shows a plot of IRI versus overall OBSI for all fourth-year measurements. The results indicate no trend between IRI and OBSI, and little difference between the three main texture types used in California with regard to that relationship.

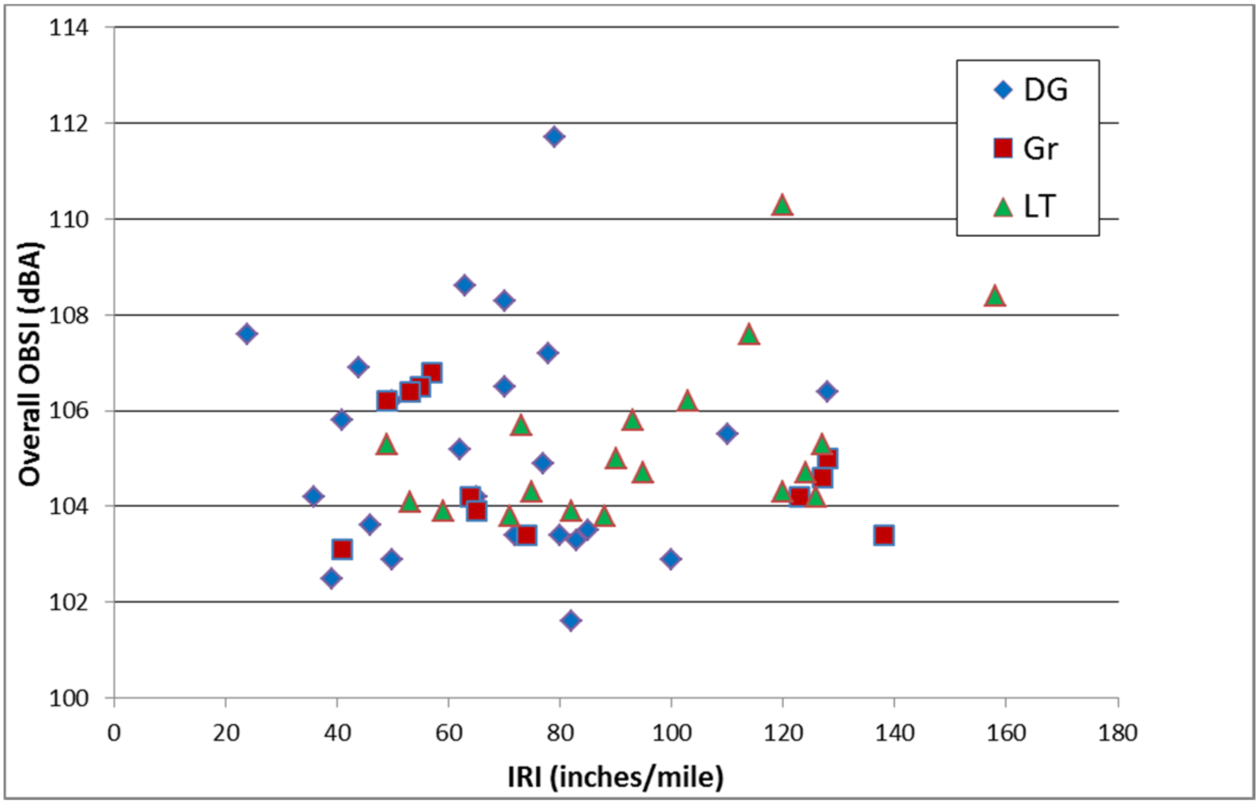

Figure 5.24: OBSI versus IRI for different texture types.
(Note: 1 m/km = 62.3 inches/mile; DG=diamond ground, Gr=diamond grooved, LT=longitudinally tined)

6 CONCLUSIONS AND RECOMMENDATIONS

The results presented in this report focus primarily on the three concrete pavement textures commonly used in California—diamond ground (DG), diamond grooved (Gr) and longitudinally tined (LT)—and to a lesser extent on the other two concrete pavement textures considered in the study—burlap drag (BD) and longitudinally broomed (LB). Based on the results of the four-year study, the following conclusions can be drawn regarding noise from tire/pavement interaction (OBSI), pavement smoothness (IRI), and surface drainability of concrete pavement textures used on the California state highway network:

1. The OBSI levels on the concrete pavements evaluated in this study ranged from 100 dBA to 112 dBA across all five texture types. This is the same as the range of OBSI levels for concrete pavement textures measured in other similar studies.
2. The average overall OBSI levels for the diamond-ground (DG), diamond-grooved (Gr), and longitudinally tined (LT) sections where the textures were not worn out ranged from 104 to 107 dBA, with DG and Gr sections typically being quieter than LT sections. For comparison, the average OBSI level for the experimental grind-and-groove textured sections was 101 dBA (reported in a separate report).
3. The average OBSI levels for the five continuously reinforced concrete pavement (CRCP) sections and the jointed plain concrete pavement (JPCP) sections were 105 and 106 dBA, respectively. However, the CRCP sections were too few for a meaningful comparison of the noise levels for these two types of concrete pavements.
4. The average frequency content of noise for the DG, Gr, and LT sections was similar, with maximum OBSI levels at 60 mph occurring between 800 and 1,000 Hz.
5. The relationship between OBSI versus age of the test sections since construction (LT) or the last retexturing (DG or Gr) showed wide scatter, indicating that age is not a good predictor of noise on concrete pavement because of environmental, traffic, and other pavement performance-related factors. However, the OBSI values for the 23 test sections with four years of measurements showed rates of increase in OBSI with age of 0.1, 0.3, and 0.8 dBA per year for the LT, Gr and DG sections, respectively.
6. The average IRI values for the DG, Gr, and LT sections with new or aged texture conditions were 68, 81, and 96 inches/mile, respectively. Although there was no correlation between OBSI and IRI, test sections with higher IRI values typically had higher OBSI levels.
7. The diamond-grooved test sections showed the fastest outflow meter times, ranging from two to five seconds, indicating a greater capacity for allowing water to move out from under the tire; this reflects a

lower potential risk for hydroplaning than the diamond-ground and longitudinally tined sections, which had substantially longer outflow meter times ranging from three to fifteen seconds.

8. The diamond-grooved sections had higher Mean Profile Depth (MPD) values (1.02 to 1.51 mm), reflecting a greater drainability capacity and lower potential risk for hydroplaning than the longitudinally tined (0.6 to 1.36 mm) and the diamond-ground (0.45 to 0.5 mm) textures.
9. The outflow meter and the MPD measurements both indicate that diamond-grooved sections had a greater capacity for allowing water to move out from under the tire. This finding suggests that diamond-grooved concrete pavements would generally be more effective in reducing the risk of hydroplaning than diamond-ground or longitudinally tined concrete pavements.

This study makes the following recommendations for the development and implementation of quieter concrete pavement strategies in California:

1. Continue to use diamond grinding and diamond grooving to retexture existing concrete pavements to improve friction, hydroplaning, and ride quality characteristics, and to reduce traffic noise.
2. Continue the development, implementation, and evaluation of the grind-and-groove strategy as a standard practice (initial pilot projects are documented in a separate report).
3. In noise sensitive areas where quieter pavement surface texture is important, this study recommends the following strategies:
    a. Use the grind-and-groove procedure to retexture pavement surface.
    b. Develop specifications for producing longitudinal tining that limit positive texture. These specifications could potentially involve the use of the laser texture scanner and the parameters identified in this study.
    c. Develop specifications for measuring tire/pavement interaction OBSI levels at the completion of new construction or pavement preservation/rehabilitation projects.
4. Caltrans should undertake a broader study to evaluate the effects of concrete pavement texturing procedures on smoothness for new construction and lane replacement projects to determine whether diamond grinding or grind-and-groove texturing might be worthwhile substitutes for longitudinal tining as a part of initial construction.

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APPENDIX A: SUMMARY TABLE OF OBSI MEASUREMENT DATES AND RESULTS

Table A.1: List of Locations, Texture Types, Conditions, Construction Date, and Dates of Measurements (for sections included in fourth year measurements only)

Section	Location***	Lane	Texture[*]	Climate Region	Traffic	Rain	Const.	Last Surfacing Year	Date of Measurement			
									Year 1	Year 2	Year 3	Year 4
QP-159	06Ker58E110.3	2 of 2	BD	Desert	Low	Low	2003	7/1/2003	1/9/2009	12/3/2009	3/23/2011	8/11/2012
ES-177	02SIS5NR57	2 of 2	DG	High Desert	Low	Low	1970	9/26/2007	Not Tested	Not Tested	Not Tested	12/18/2012
QP-131	11SD8W15.5	1 of 3	DG	South Coast	High	Low	1985	7/1/1997	11/11/2008	11/23/2009	12/15/2010	12/19/2012
QP-132	11SD805N2.1	5 of 5	DG	South Coast	High	Low	1975	7/1/1998	11/12/2008	11/24/2009	12/16/2010	8/12/2012
QP-133	11SD805N2.3	4 of 4	DG	South Coast	High	Low	1975	7/1/1998	11/12/2008	11/24/2009	12/16/2010	8/12/2012
QP-147	04SM280N11.6	1 of 3	DG	Central Coast	High	Low	1973	7/1/2007	12/2/2008	11/16/2009	3/1/2011	9/12/2012
QP-148	04SM280N1.6	1 of 4	DG	Central Coast	High	Low	1969	7/1/2001	12/3/2008	11/16/2009	4/19/2011	4/11/2013
QP-155	06Ker58E110.6	2 of 2	DG	Desert	Low	Low	2003	7/1/2006	1/8/2009	12/2/2009	3/23/2011	10/9/2013
QP-160	06Ker58E110	2 of 2	DG	Desert	Low	Low	2003	7/1/2006	2/23/2009	12/2/2009	3/23/2011	8/11/2012
QP-166	06Ker58E111.7	2 of 2	DG	Desert	Low	Low	2003	7/1/2006	2/26/2009	12/2/2009	3/22/2011	12/20/2012
QP-181	11IMP8W87.58	2 of 2	DG	Desert	Low	Low	1970	2/1/2004	Not Tested	Not Tested	Not Tested	8/13/2012
QP-182	11IMP8W63	2 of 2	DG	Desert	Low	Low	1969	2/1/2004	Not Tested	Not Tested	Not Tested	8/13/2012
QP-183	11IMP8E58	2 of 2	DG	Desert	Low	Low	1969	2/1/2004	Not Tested	Not Tested	Not Tested	8/13/2012
QP-184	08RIV15N15.74	3 of 3	DG	Desert	High	Low	1985	3/25/2009	Not Tested	Not Tested	Not Tested	8/14/2012
QP-185	08RIV15S15.75	3 of 3	DG	Desert	High	Low	1985	3/25/2009	Not Tested	Not Tested	Not Tested	8/14/2013
QP-186	04SON12W13.38	2 of 2	DG	Low Mountain	Low	High	1964	2/8/2001	Not Tested	Not Tested	Not Tested	8/31/2012
QP-188	04SON12W15.3	2 of 2	DG	Low Mountain	High	High	1964	2/8/2001	Not Tested	Not Tested	Not Tested	8/31/2012
QP-193**	02SIS5N3	2 of 2	DG	Low Mountain	Low	High	1964	7/15/2011	Not Tested	Not Tested	Not Tested	3/27/2013
QP-194	03ED50E5.5	3 of 3	DG	Low Mountain	High	High	1970	1/4/2013	Not Tested	Not Tested	Not Tested	4/11/2013
QP-195	03ED50E6	3 of 3	DG	Low Mountain	High	High	1970	1/4/2013	Not Tested	Not Tested	Not Tested	4/11/2013
QP-196	04SON101N40.5	2 of 2	DG	Low Mountain	Low	High	1975	9/17/2001	Not Tested	Not Tested	Not Tested	4/12/2013
QP-197	04SON101N50.33	2 of 2	DG	Low Mountain	Low	High	1994	3/2/2012	Not Tested	Not Tested	Not Tested	4/12/2013
QP-198	04SON101S50.5	2 of 2	DG	Low Mountain	Low	High	1994	3/2/2012	Not Tested	Not Tested	Not Tested	4/12/2013
QP-200	03BUT99S35.9	2 of 2	DG	Inland Valley	Low	Low	1966	12/7/2011	Not Tested	Not Tested	Not Tested	11/13/2013
QP-204	05MON101S83	2 of 2	DG	Inland Valley	Low	Low	1964	9/11/2001	Not Tested	Not Tested	Not Tested	11/18/2013

Section	Location***	Lane	Texture*	Climate Region	Traffic	Rain	Const.	Last Surfacing Year	Date of Measurement			
									Year 1	Year 2	Year 3	Year 4
QP-207	06FRE41S23.7	4 of 4	DG	Inland Valley	High	Low	1974	12/3/2007	Not Tested	Not Tested	Not Tested	11/22/2013
QP-208	06FRE41S32.17	2 of 2	DG	Inland Valley	Low	Low	1989	12/3/2007	Not Tested	Not Tested	Not Tested	11/22/2013
ES-171	12ORA91E18.4	4 of 4	Gr	South Coast	High	Low	1971	7/24/2007	Not Tested	Not Tested	Not Tested	12/18/2012
ES-172	12ORA57S21.17	4 of 4	Gr	South Coast	High	Low	1971	5/27/2003	Not Tested	Not Tested	Not Tested	12/18/2012
ES-173	12ORA57S20.85	4 of 4	Gr	South Coast	High	Low	1971	5/27/2003	Not Tested	Not Tested	Not Tested	12/18/2012
ES-174	12ORA57N13.92	4 of 4	Gr	South Coast	High	Low	1974	5/27/2003	Not Tested	Not Tested	Not Tested	12/18/2012
QP-103	03Yol50E0.2	1 of 4	Gr	Inland Valley	High	Low	1969	7/1/2005	10/2/2008	Not Tested	Not Tested	12/16/2012
QP-128	04SCL85N14.8	3 of 3	Gr	Central Coast	High	Low	1993	7/1/2006	11/7/2008	11/18/2009	4/20/2011	12/16/2012
QP-134	11SD905W2.5	2 of 2	Gr	South Coast	High	Low	1975	7/1/2000	11/12/2008	11/24/2009	12/16/2010	9/12/2012
QP-153	10MER99S17.5	1 of 2	Gr	Inland Valley	Low	Low	1962	7/1/2006	12/17/2008	11/13/2009	2/24/2011	11/14/2013
QP-154	06Ker58S110.2	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	1/8/2009	12/2/2009	3/22/2011	8/30/2012
QP-156	06Ker58E111.2	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	1/9/2009	12/2/2009	3/22/2011	12/20/2012
QP-157	06Ker58E114.4	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	1/9/2009	12/2/2009	3/23/2011	8/10/2012
QP-161	06Ker58E110.4	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	2/23/2009	12/3/2009	3/23/2011	10/9/2013
QP-162	06Ker58E111.5	2 of 2	LB	Desert	Low	Low	2003	7/1/2003	2/24/2009	12/3/2009	3/23/2011	10/9/2013
ES-178	06KER5S40	2 of 2	LT	Inland Valley	High	Low	1970	8/23/2010	Not Tested	Not Tested	Not Tested	12/18/2012
ES-180	11IMP78ER15.0	2 of 2	LT	Desert	Low	Low	2012	1/1/2012	Not Tested	Not Tested	Not Tested	12/18/2012
ES-181	11IMP86SR24.2	2 of 2	LT	Desert	Low	Low	2012	1/2/2012	Not Tested	Not Tested	Not Tested	12/18/2012
QP-100	03Yol113N3	2 of 2	LT	Inland Valley	Low	Low	1976	7/1/1976	9/3/2008	9/4/2009	10/5/2010	12/18/2012
QP-101	03Yol113N6	2 of 2	LT	Inland Valley	Low	Low	1990	7/1/1990	9/23/2008	9/4/2009	10/5/2010	12/18/2012
QP-108	03Pla80E45	1 of 2	LT	High Mountain	Low	High	1961	7/1/2004	10/21/2008	9/16/2009	6/20/2011	12/16/2012
QP-117	04CC80W10.3	4 of 4	LT	Central Coast	High	Low	2007	7/1/2007	10/28/2008	10/29/2009	2/9/2011	12/16/2012
QP-129	06FRE180W55.7	3 of 3	LT	Inland Valley	Low	Low	2008	7/1/2008	11/10/2008	11/13/2009	2/24/2011	3/28/2013
QP-158	06Ker58E109.5	2 of 2	LT	Desert	Low	Low	2003	7/1/2003	1/9/2009	12/2/2009	3/22/2011	8/11/2012
QP-187	04SON12E16.5	2 of 2	LT	Low Mountain	High	High	1986	2/8/2001	Not Tested	Not Tested	Not Tested	8/31/2012
QP-189	08SBD15N54	3 of 3	LT	Desert	High	Low	1964	7/1/2005	Not Tested	Not Tested	Not Tested	12/17/2012
QP-190	08SBD15S55	3 of 3	LT	Desert	Low	Low	1964	7/1/2005	Not Tested	Not Tested	Not Tested	12/17/2012
QP-191	06FRE41SR13.0	2 of 2	LT	Inland Valley	High	Low	1999	5/3/1999	Not Tested	Not Tested	Not Tested	4/11/2013

Section	Location***	Lane	Texture*	Climate Region	Traffic	Rain	Const.	Last Surfacing Year	Date of Measurement			
									Year 1	Year 2	Year 3	Year 4
QP-192	06FRE41SR11.0	2 of 2	LT	Inland Valley	High	Low	1998	9/25/1998	Not Tested	Not Tested	Not Tested	12/19/2012
QP-199	03NEV80E5.57	1 of 2	LT	High Mountain	Low	High	2006	11/22/2006	Not Tested	Not Tested	Not Tested	10/1/2013
QP-201	03BUT99S32	2 of 2	LT	Inland Valley	High	Low	1965	12/7/2011	Not Tested	Not Tested	Not Tested	11/13/2013
QP-202	03BUT99S27	2 of 2	LT	Inland Valley	Low	Low	1990	11/30/2001	Not Tested	Not Tested	Not Tested	11/13/2013
QP-203	03PLA80E56.45	1 of 2	LT	High Mountain	Low	High	2012	4/1/2012	Not Tested	Not Tested	Not Tested	11/14/2013
QP-205	05MON101N88.2	2 of 2	LT	Inland Valley	Low	Low	1964	1/16/2007	Not Tested	Not Tested	Not Tested	11/18/2013
QP-206	06FRE41N17	2 of 2	LT	Inland Valley	Low	Low	1999	8/2/1999	Not Tested	Not Tested	Not Tested	11/21/2013

Notes:
* Continuously reinforced concrete sections shown with shading, all other sections are jointed plain concrete.
** QP-193 dropped from analysis because of excessive chain wear.

Table A.2: List of Locations, Texture Types, Conditions, Construction Date, Age at Measurement, Overall OBSI for All Four Years of Measurements and IRI in Fourth Year of Measurement (for sections included in fourth year measurements only)

Section	Location	Lane	Texture*	Climate Region	Traffic	Rain	Const.	Last Surfacing Year	Age at Time of Measurement				Overall OBSI Level (dBA)				IRI	
									Year 1	Year 2	Year 3	Year 4	Year 1	Year 2	Year 3	Year 4	Year 4 (in/mi)	Year 4 (m/km)
QP-159	06Ker58E110.3	2 of 2	BD	Desert	Low	Low	2003	7/1/2003	6	7	8	10	101.9	102.2	103.9	103.1	65	1.04
ES-177	02SIS5NR57	2 of 2	DG	High Desert	Low	Low	1970	9/26/2007	Not Tested	Not Tested	Not Tested	6				106.0		
QP-131	11SD8W15.5	1 of 3	DG	South Coast	High	Low	1985	7/1/1997	11	12	13	16	105.3	103.7	104.3	111.7	79	1.27
QP-132	11SD805N2.1	5 of 5	DG	South Coast	High	Low	1975	7/1/1998	10	11	12	15	105.4	106.3	107.1	101.6	82	1.31
QP-133	11SD805N2.3	4 of 4	DG	South Coast	High	Low	1975	7/1/1998	10	11	12	15	106.5	106.4	106.9	104.2	36	0.57
QP-147	04SM280N11.6	1 of 3	DG	Central Coast	High	Low	1973	7/1/2007	1	2	4	6	102.5	102.9	103.3	106.5	70	1.12
QP-148	04SM280N1.6	1 of 4	DG	Central Coast	High	Low	1969	7/1/2001	7	8	10	12	102.9	103.4	104.1	102.9	100	1.6
QP-155	06Ker58E110.6	2 of 2	DG	Desert	Low	Low	2003	7/1/2006	3	4	5	7	101.2	101.7	103.4	105.8	41	0.66
QP-160	06Ker58E110	2 of 2	DG	Desert	Low	Low	2003	7/1/2006	3	4	5	7	102.7	102.9	104.5	107.6	24	0.39
QP-166	06Ker58E111.7	2 of 2	DG	Desert	Low	Low	2003	7/1/2006	3	4	5	7	101.7	103	103.3	106.9	44	0.71
QP-181	11IMP8W87.58	2 of 2	DG	Desert	Low	Low	1970	2/1/2004	Not Tested	Not Tested	Not Tested	9				103.3	83	1.33
QP-182	11IMP8W63	2 of 2	DG	Desert	Low	Low	1969	2/1/2004	Not Tested	Not Tested	Not Tested	9				102.9	50	0.8
QP-183	11IMP8E58	2 of 2	DG	Desert	Low	Low	1969	2/1/2004	Not Tested	Not Tested	Not Tested	9				103.4	80	1.28
QP-184	08RIV15N15.74	3 of 3	DG	Desert	High	Low	1985	3/25/2009	Not Tested	Not Tested	Not Tested	4				104.2	65	1.05
QP-185	08RIV15S15.75	3 of 3	DG	Desert	High	Low	1985	3/25/2009	Not Tested	Not Tested	Not Tested	4				104.9	77	1.23
QP-186	04SON12W13.38	2 of 2	DG	Low Mountain	Low	High	1964	2/8/2001	Not Tested	Not Tested	Not Tested	12				103.5	85	1.37
QP-188	04SON12W15.3	2 of 2	DG	Low Mountain	High	High	1964	2/8/2001	Not Tested	Not Tested	Not Tested	12				103.4	72	1.16
QP-193**	02SIS5N3	2 of 2	DG	Low Mountain	Low	High	1964	7/15/2011	Not Tested	Not Tested	Not Tested	2				112.0		
QP-194	03ED50E5.5	3 of 3	DG	Low Mountain	High	High	1970	1/4/2013	Not Tested	Not Tested	Not Tested	0				107.2	78	1.25
QP-195	03ED50E6	3 of 3	DG	Low Mountain	High	High	1970	1/4/2013	Not Tested	Not Tested	Not Tested	0				108.3	70	1.13
QP-196	04SON101N40.5	2 of 2	DG	Low Mountain	Low	High	1975	9/17/2001	Not Tested	Not Tested	Not Tested	12				105.5	110	1.77
QP-197	04SON101N50.33	2 of 2	DG	Low Mountain	Low	High	1994	3/2/2012	Not Tested	Not Tested	Not Tested	1				102.5	39	0.62
QP-198	04SON101S50.5	2 of 2	DG	Low Mountain	Low	High	1994	3/2/2012	Not Tested	Not Tested	Not Tested	1				103.6	46	0.74
QP-200	03BUT99S35.9	2 of 2	DG	Inland Valley	Low	Low	1966	12/7/2011	Not Tested	Not Tested	Not Tested	2				106.4	128	2.06
QP-204	05MON101S83	2 of 2	DG	Inland Valley	Low	Low	1964	9/11/2001	Not Tested	Not Tested	Not Tested	12				108.6	63	1.01

Section	Location	Lane	Texture*	Climate Region	Traffic	Rain	Const.	Last Surfacing Year	Age at Time of Measurement				Overall OBSI Level (dBA)				IRI	
									Year 1	Year 2	Year 3	Year 4	Year 1	Year 2	Year 3	Year 4	Year 4 (in/mi)	Year 4 (m/km)
QP-207	06FRE41S23.7	4 of 4	DG	Inland Valley	High	Low	1974	12/3/2007	Not Tested	Not Tested	Not Tested	6				106.2	50	0.8
QP-208	06FRE41S32.17	2 of 2	DG	Inland Valley	Low	Low	1989	12/3/2007	Not Tested	Not Tested	Not Tested	6				105.2	62	1
ES-171	12ORA91E18.4	4 of 4	Gr	South Coast	High	Low	1971	7/24/2007	Not Tested	Not Tested	Not Tested	6				104.2	123	1.97
ES-172	12ORA57S21.17	4 of 4	Gr	South Coast	High	Low	1971	5/27/2003	Not Tested	Not Tested	Not Tested	10				103.1	41	0.66
ES-173	12ORA57S20.85	4 of 4	Gr	South Coast	High	Low	1971	5/27/2003	Not Tested	Not Tested	Not Tested	10				106.8	57	0.91
ES-174	12ORA57N13.92	4 of 4	Gr	South Coast	High	Low	1974	5/27/2003	Not Tested	Not Tested	Not Tested	10				104.6	127	2.04
QP-103	03Yol50E0.2	1 of 4	Gr	Inland Valley	High	Low	1969	7/1/2005	3	Not Tested	Not Tested	8	99.9			106.5	55	0.89
QP-128	04SCL85N14.8	3 of 3	Gr	Central Coast	High	Low	1993	7/1/2006	2	3	5	7	103	104.2	104.3	106.4	53	0.85
QP-134	11SD905W2.5	2 of 2	Gr	South Coast	High	Low	1975	7/1/2000	8	9	10	13	105	106.4	106.5	105.0	128	2.06
QP-153	10MER99S17.5	1 of 2	Gr	Inland Valley	Low	Low	1962	7/1/2006	2	3	5	7	105.1	106.1	106.9	103.4	138	2.21
QP-154	06Ker58S110.2	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	3	4	5	7	102.1	103.7	103.6	104.2	64	1.02
QP-156	06Ker58E111.2	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	3	4	5	7	103.7	104.7	105.9	106.2	49	0.78
QP-157	06Ker58E114.4	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	3	4	5	7	102.1	103.2	105.1	103.4	74	1.19
QP-161	06Ker58E110.4	2 of 2	Gr	Desert	Low	Low	2003	7/1/2006	3	4	5	7	103.2	103.2	104.3	103.9	65	1.04
QP-162	06Ker58E111.5	2 of 2	LB	Desert	Low	Low	2003	7/1/2003	6	7	8	10	102.5	103	104.4	104.8	89	1.43
ES-178	06KER5S40	2 of 2	LT	Inland Valley	High	Low	1970	8/23/2010	Not Tested	Not Tested	Not Tested	3				103.8	88	1.41
ES-180	11IMP78ER15.0	2 of 2	LT	Desert	Low	Low	2012	1/1/2012	Not Tested	Not Tested	Not Tested	1				104.1	53	0.85
ES-181	11IMP86SR24.2	2 of 2	LT	Desert	Low	Low	2012	1/2/2012	Not Tested	Not Tested	Not Tested	1				105.3	49	0.79
QP-100	03Yol113N3	2 of 2	LT	Inland Valley	Low	Low	1976	7/1/1976	32	33	34	37	103.1	105.3	104.9	104.2	126	2.02
QP-101	03Yol113N6	2 of 2	LT	Inland Valley	Low	Low	1990	7/1/1990	18	19	20	23	105.2	106.7	106	103.9	59	0.95
QP-108	03Pla80E45	1 of 2	LT	High Mountain	Low	High	1961	7/1/2004	4	5	7	9	104.5	105.8	106.5	104.7		
QP-117	04CC80W10.3	4 of 4	LT	Central Coast	High	Low	2007	7/1/2007	1	2	4	6	103.1	106.3	105	105.3	127	2.04
QP-129	06FRE180W55.7	3 of 3	LT	Inland Valley	Low	Low	2008	7/1/2008	0	1	3	5	103.6	105	105.5	103.9	82	1.32
QP-158	06Ker58E109.5	2 of 2	LT	Desert	Low	Low	2003	7/1/2003	6	7	8	10	103.6	104.4	105.4	103.8	71	1.14
QP-187	04SON12E16.5	2 of 2	LT	Low Mountain	High	High	1986	2/8/2001	Not Tested	Not Tested	Not Tested	12				104.3	120	1.93
QP-189	08SBD15N54	3 of 3	LT	Desert	High	Low	1964	7/1/2005	Not Tested	Not Tested	Not Tested	8				104.7	124	1.99
QP-190	08SBD15S55	3 of 3	LT	Desert	Low	Low	1964	7/1/2005	Not Tested	Not Tested	Not Tested	8				104.7	95	1.52

Section	Location	Lane	Texture*	Climate Region	Traffic	Rain	Const.	Last Surfacing Year	Age at Time of Measurement				Overall OBSI Level (dBA)				IRI	
									Year 1	Year 2	Year 3	Year 4	Year 1	Year 2	Year 3	Year 4	Year 4 (in/mi)	Year 4 (m/km)
QP-191	06FRE41SR13.0	2 of 2	LT	Inland Valley	High	Low	1999	5/3/1999	Not Tested	Not Tested	Not Tested	14				106.2	103	1.65
QP-192	06FRE41SR11.0	2 of 2	LT	Inland Valley	High	Low	1998	9/25/1998	Not Tested	Not Tested	Not Tested	15				105.0	90	1.44
QP-199	03NEV80E5.57	1 of 2	LT	High Mountain	Low	High	2006	11/22/2006	Not Tested	Not Tested	Not Tested	7				104.3	75	1.2
QP-201	03BUT99S32	2 of 2	LT	Inland Valley	High	Low	1965	12/7/2011	Not Tested	Not Tested	Not Tested	2				107.6	114	1.83
QP-202	03BUT99S27	2 of 2	LT	Inland Valley	Low	Low	1990	11/30/2001	Not Tested	Not Tested	Not Tested	12				110.3	120	1.93
QP-203	03PLA80E56.45	1 of 2	LT	High Mountain	Low	High	2012	4/1/2012	Not Tested	Not Tested	Not Tested	1				105.7	73	1.17
QP-205	05MON101N88.2	2 of 2	LT	Inland Valley	Low	Low	1964	1/16/2007	Not Tested	Not Tested	Not Tested	6				108.4	158	2.54
QP-206	06FRE41N17	2 of 2	LT	Inland Valley	Low	Low	1999	8/2/1999	Not Tested	Not Tested	Not Tested	14				105.8	93	1.49

Notes:
* Continuously reinforced concrete sections shown with shading, all other sections are jointed plain concrete.
**QP-193 dropped from analysis because of excessive chain wear.

APPENDIX B: CORRELATION OF TEST TIRES AND NOISE ANALYZERS USED IN DIFFERENT YEARS OF MEASUREMENT

Appendix B.1: Overview

Over the years that that on-board sound intensity measurement technology has been used by UCPRC, there have been improvements to the process of OBSI data collection. As with the research performed in previous years, adjustments to the Year 4 OBSI data have been made to normalize the results and make them consistent with other OBSI results from prior years. These adjustments include the following:

a. Test tire: Although the tires used in all four years of data collection were Standard Reference Test Tires (SRTTs), an actual new SRTT was introduced in December 2011 and was used for the 2012/2013 testing presented in this report to prevent the problems associated with using an aged tire. Through comparisons performed later, linear transformation equations were developed—using only concrete test sections—to adjust the results from Year 1, Year 2, Year 3, and Year 4 tires other than SRTT#1 back to the first SRTT used by the UCPRC research team, the standard reference tire for all UCPRC noise studies. Use of a common reference tire (SRTT#1) allows the eventual comparison of all noise measurements, regardless of surface type. The conversions were applied frequency by frequency, and the overall sound intensity was calculated from its own linear transformation as well, not from summation of the adjusted spectra values.

b. Sound analyzer: A frequency-by-frequency correction was applied to account for the fact that a new sound analyzer was introduced into the study in the second year and was used from then on. Year 1 OBSI data were measured using two Larson Davis two-channel analyzers, but they were replaced with a Harmonie four-channel analyzer in Year 2, Year 3, and Year 4 of this study using data from both asphalt and concrete sections; this was possible because there was no interaction of surface type and the two analyzers. Linear transformation equations were determined using results from the field sections tested with both analyzers, and the results that had previously been measured with the Larson Davis analyzers were converted to equivalent Harmonie analyzer results. No significant influence on the conversion was found from pavement type, and an equation combining data from both pavement types was developed and used on all sections. Despite discussions with the manufacturers and Dr. Paul Donavan of Illingworth and Rodkin, it could not be determined why the 400 Hz frequency had a low correlation coefficient between the two analyzers. The 400 Hz frequency data was included in the overall OBSI correlation because it did show an expected trend and it has been general practice in UCPRC and other pavement noise studies to include it, although there was more variance around that trend than for the other frequencies. Removing the 400 Hz frequency could have introduced bias into the overall OBSI correlation despite that frequency having a low weighting in the dBA system. The analyzer adjustment equations are presented in Appendix B.

The decision to change tires between the first two years of data collection was made in the summer of 2009 based on an observation that the large number of sections tested by the UCPRC each year was producing observable wear on the tread. There were no guidelines at the time for when to change tires. In early 2012, Donavan and Lodico *(B1)* presented a paper at the Transportation Research Board conference based on measurements performed as part of NCHRP Project 1-41(1) *(B2)* that included preliminary suggested guidelines for when to change tires. That paper states that "potential criteria for retiring a test tire are: 1) being in-service for more than 4 years, 2) having more than 11,000 miles, 3) having hardness number of greater than 68, and 4) having tread depth less than 7.2 mm." The paper also states that "These could be applied singly or concurrently such that if two or more are violated, the tire replacement should be considered."

In early February 2012, UCPRC examined the ages, miles put on each tire per year, hardness values recorded over time (UCPRC measures hardness on all tires in inventory several times each year), and tread depths measured over time (also recorded several times each year). It was found that the tire used in Year 1 of this study met criteria 2, 3, and 4 noted above. Based on Donavan and Lodico's proposed guidelines, the UCPRC decision to change the tire between the different testing periods of the study (2009, 2010/2011, 2012/2013), and each year subsequently, was justified.

The paper by Donavan and Lodico also recommends the collection of data relating the properties of different SRTT tires, such as age, travelled miles, hardness, and tread depths in order to better understand how they affect OBSI measurements in a database. This was already part of the standard practice for the annual calibration of the new UCPRC tire to previously used tires. The current UCPRC practices of measuring hardness and tread depth, tracking accumulated miles, and developing both frequency-by-frequency and overall OBSI statistical correlations between tires also provided inputs for that database, making it available for further standardizing the AASHTO OBSI test method, and to help develop specifications if Caltrans ever considers implementing OBSI measurement as a part of acceptance of constructed pavement surfaces.

Appendix B.2: Test Tire Correlations

A set of experiments was conducted on several pavement sections around Los Angeles and Davis, California, during May and June 2010, 2011, and 2012, to investigate the relationship between the four SRTT tires (SRTT#A [#1], SRTT#B [#2], SRTT#3, and SRTT#4 and SRTT#5) in on-board sound intensity (OBSI). These pavement sections were included: ODR-N, ODR-S, RD105-N, RD105-S, RD32a-E, RD32a-W1, and RD32a-W2 near Davis. Figure B.1 and Figure B.2 show the comparison between sound intensities measured using the different test tires on asphalt (AC) and concrete (PCC) sections. Simple linear regression analysis was conducted for various pairs of SRTT tires, for AC sections only and for PCC sections only. The results are summarized Table B.1 and Table B.2, respectively.

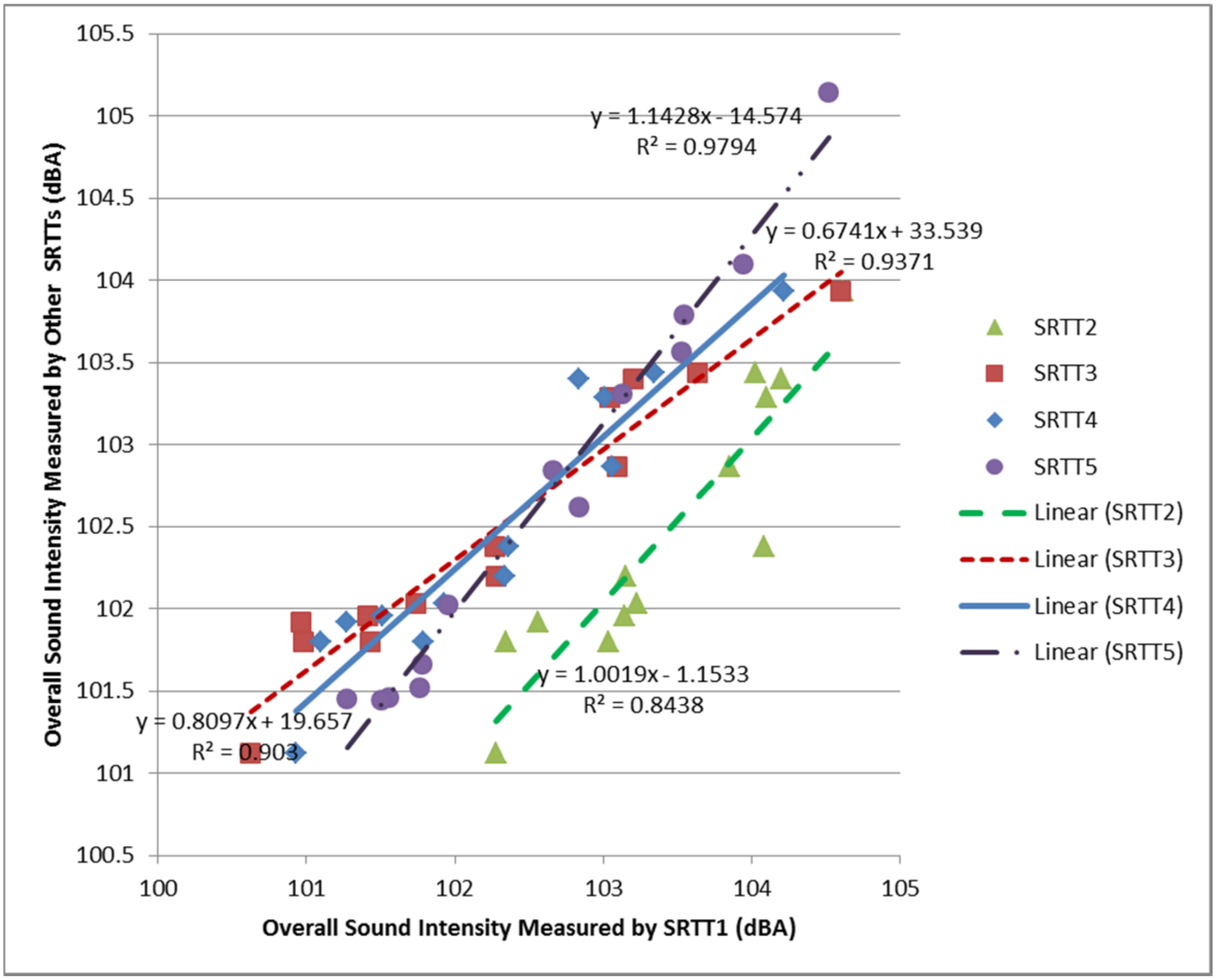

Figure B.1: Comparison of overall OBSI measured with various SRTT tires on AC pavements.

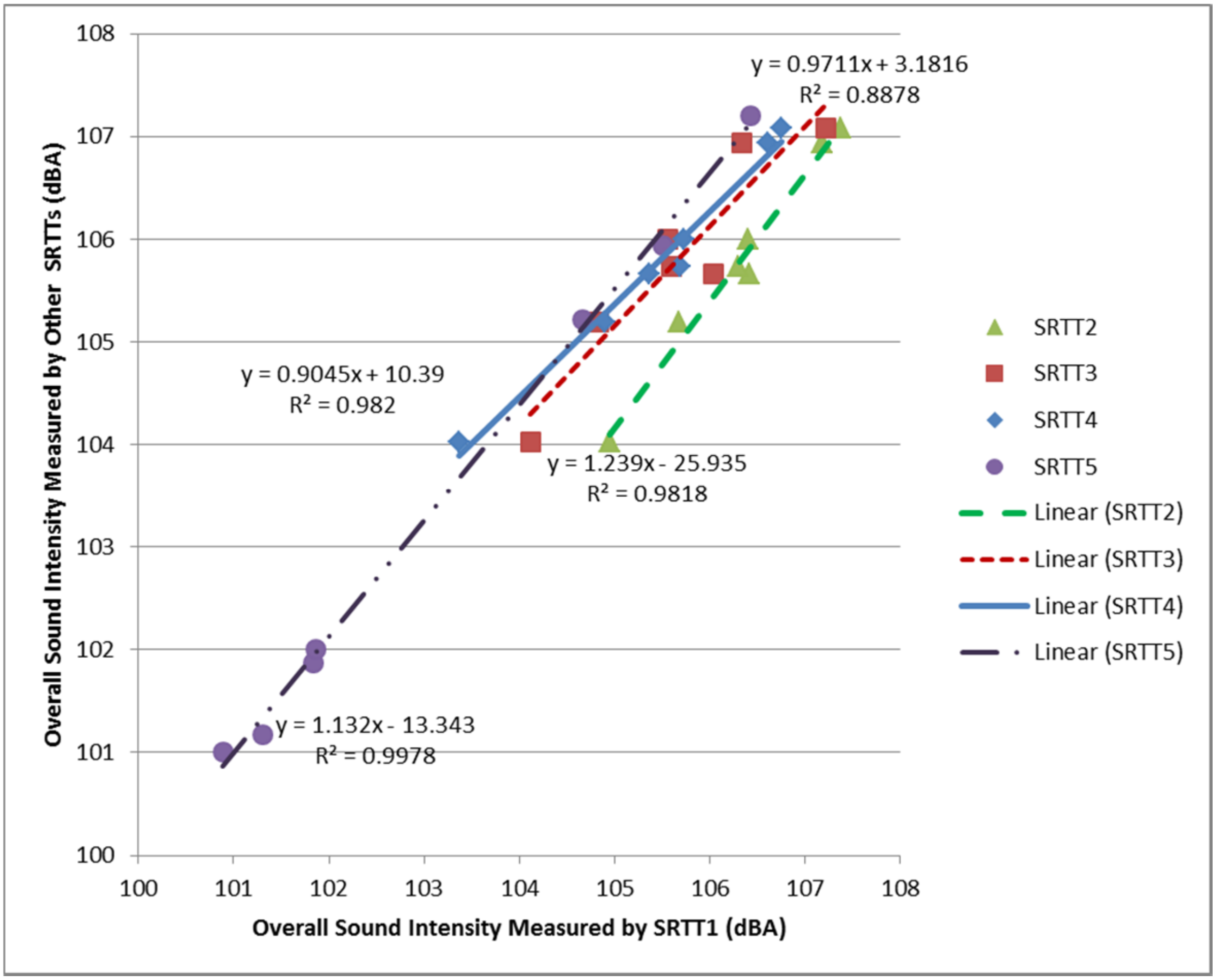

Figure B.2: Comparison of overall OBSI measured with various SRTT tires on PCC pavements.

Table B.1: SRTT Tire Calibration Parameters on AC Pavements

	SRTT#2 to SRTT#1			SRTT#3 to SRTT#1		
Frequency	Intercept	Slope	R^2	Intercept	Slope	R^2
400	14.243	0.837	0.65	45.563	0.461	0.17
500	1.445	0.978	0.69	23.027	0.736	0.75
630	-14.686	1.158	0.76	19.177	0.792	0.85
800	-5.616	1.052	0.86	24.354	0.752	0.95
1,000	-2.906	1.014	0.85	28.273	0.705	0.89
1,250	6.818	0.916	0.76	32.456	0.659	0.73
1,600	-5.961	1.053	0.96	34.172	0.634	0.95
2,000	6.439	0.918	0.98	27.032	0.703	0.95
2,500	14.527	0.824	0.93	33.542	0.614	0.86
3,150	12.363	0.842	0.86	36.138	0.562	0.83
4,000	14.408	0.812	0.88	31.576	0.602	0.90
5,000	14.833	0.801	0.84	30.712	0.598	0.93
Overall	-1.153	1.002	0.84	33.539	0.674	0.94
	SRTT#4 to SRTT#1			**SRTT#5 to SRTT#1**		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	39.221	0.530	0.10	27.978	0.677	0.65
500	2.215	0.974	0.74	-8.742	1.097	0.67
630	-14.408	1.152	0.79	-9.734	1.108	0.88
800	10.589	0.890	0.91	-24.250	1.249	0.96
1,000	14.778	0.849	0.89	-9.569	1.096	0.98
1,250	31.583	0.671	0.60	-1.575	1.019	0.96
1,600	27.946	0.703	0.91	8.776	0.913	0.99
2,000	12.487	0.867	0.93	-5.887	1.075	0.98
2,500	23.362	0.733	0.86	-6.563	1.080	0.98
3,150	28.459	0.654	0.74	-11.408	1.144	0.98
4,000	22.056	0.720	0.86	-11.793	1.157	0.96
5,000	21.771	0.711	0.91	-10.811	1.158	0.98
Overall	19.657	0.810	0.90	-14.574	1.143	0.98

Table B.2: SRTT Tire Calibration Parameters on PCC Pavements

	SRTT#2 to SRTT#1			SRTT#3 to SRTT#1		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	0.772	1.004	0.73	23.847	0.735	0.81
500	-3.033	1.032	0.95	-10.202	1.117	0.85
630	1.374	0.987	0.98	-2.912	1.035	0.92
800	-5.173	1.050	0.99	-9.376	1.095	0.96
1,000	5.223	0.938	0.68	3.293	0.966	0.99
1,250	-1.000	1.002	0.97	4.195	0.958	0.94
1,600	-5.256	1.048	0.98	14.262	0.851	0.95
2,000	-6.638	1.060	0.96	8.604	0.909	0.95
2,500	1.452	0.974	0.97	7.992	0.909	0.96
3,150	-1.296	1.009	0.97	16.262	0.807	0.94
4,000	-0.307	1.001	0.97	14.062	0.830	0.93
5,000	0.387	0.996	0.97	10.427	0.868	0.92
Overall	-25.935	1.239	0.98	3.182	0.971	0.89

	SRTT#4 to SRTT#1			SRTT#5 to SRTT#1		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	0.165	0.999	0.96	-1.954	1.020	0.95
500	-5.181	1.059	0.95	-8.873	1.108	0.98
630	1.911	0.979	0.97	-5.693	1.076	0.99
800	2.978	0.971	0.98	-13.890	1.146	1.00
1,000	18.903	0.811	0.96	-5.125	1.049	0.98
1,250	1.902	0.987	0.96	7.733	0.922	0.96
1,600	14.482	0.856	0.99	5.571	0.950	0.99
2,000	7.213	0.933	1.00	-17.911	1.205	0.99
2,500	4.920	0.950	0.99	-103.542	2.187	0.91
3,150	6.546	0.926	0.99	-64.698	1.791	0.80
4,000	6.093	0.930	0.99	50.546	0.361	0.06
5,000	7.561	0.908	0.98	0.650	0.999	0.24
Overall	10.390	0.905	0.98	-13.343	1.132	1.00

Appendix B.3: Sound Analyzer Correlations

A set of experiments was performed in 2010 to investigate the relationship between the Larson Davis and Harmonie analyzers. It was believed that the calibration between analyzer equipment types is independent of pavement type and tire type, which was found to be true. Simple linear regression analysis was conducted on the data from the four experiments. The results are summarized in Table B.3.

Table B.3: Equipment Calibration Parameters on AC and PCC Pavements

Frequency	Intercept	Slope	R^2
400	14.0606	0.8298	0.67
500	0.5176	0.9901	0.95
630	1.3928	0.9792	0.95
800	5.0341	0.9451	0.95
1,000	-0.2779	0.9997	0.97
1,250	3.6008	0.9597	0.95
1,600	2.2686	0.9735	0.97
2,000	1.7017	0.9797	0.96
2,500	1.3379	0.9835	0.95
3,150	1.9084	0.9763	0.92
4,000	2.3261	0.9694	0.92
5,000	4.3423	0.9402	0.89
Overall	2.1918	0.9758	0.97

Note: OBSI(Harmonie) = OBSI(Larson Davis)*Slope + Intercept

Appendix B.4: Calibration of OBSI Data for This Report

After reviewing the first five-year AC data analysis and the calibration equations developed in this section and in other studies, Caltrans and UCPRC reached an agreement regarding how to handle the calibration of OBSI data for the fourth-year concrete noise report. It was agreed that UCPRC would take these steps in preparing the data for the fourth-year concrete noise report:

1. Disregard calibration for pavement temperature.
2. Remove all OBSI data measured at a test car speed other than 60 mph.
3. Calibrate the first concrete noise data from Larson Davis to Sinus Harmonie equipment using the parameters in Table B.3.
4. Calibrate the data from the first-, second-, third-, and fourth-year data from their respective SRTT tire to SRTT#1 using the parameters in Table B.2.
5. Calibrate all data for air density.

The reference conditions for OBSI data in this report are 60 mph test car speed, SRTT#1 tire, and Sinus Harmonie analyzer.

Appendix B.5: References

B1. Donavan, P., and D. Lodico. (2012). *Variation in On-Board Sound Intensity Levels Created by Different ASTM Standard Reference Test Tires*. 91st Transportation Research Board Annual Meeting 2012, Paper #12-4130. Transportation Research Board, Washington, D.C.

B2. Donavan, P., and D. Lodico. (2011). Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement Project. National Cooperative Highway Research Program Project 1-44 (1). National Academy of Science, Washington, D.C.

APPENDIX C: OBSI AND IRI BAR CHARTS

The overall OBSI levels of each section that was measured in the fourth-year factorial are shown here for Year 1, Year 2, and Year 3. The fourth-year plot includes all sections measured in the fourth-year factorial.

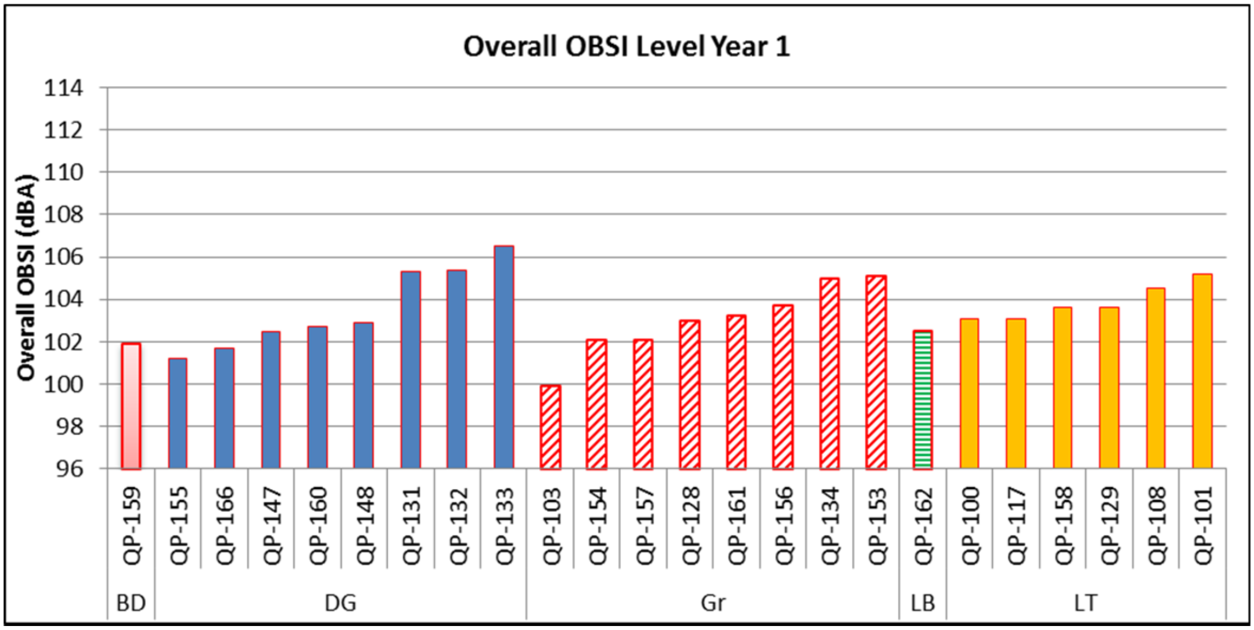

Figure C.1: OBSI for each section measured in Year 1 sorted by texture type and OBSI level, for sections with fourth year measurements.

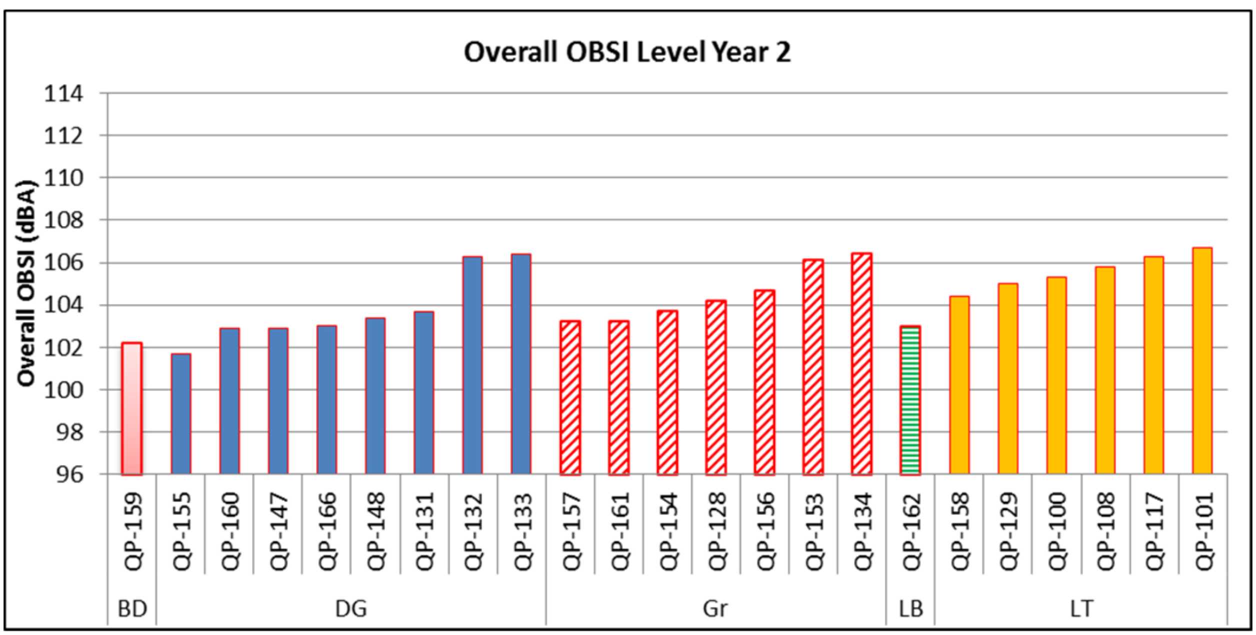

Figure C.2: OBSI for each section measured in Year 2 sorted by texture type and OBSI level, for sections with fourth year measurements.

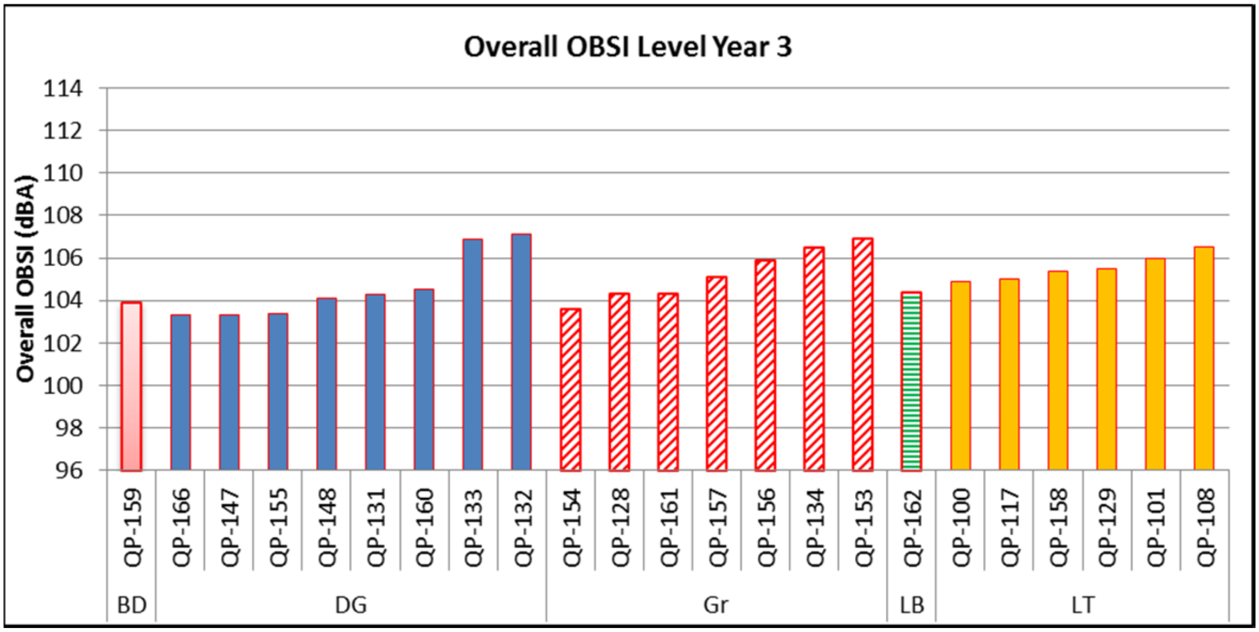

Figure C.3: OBSI for each section measured in Year 3 sorted by texture type and OBSI level, for sections with fourth year measurements.

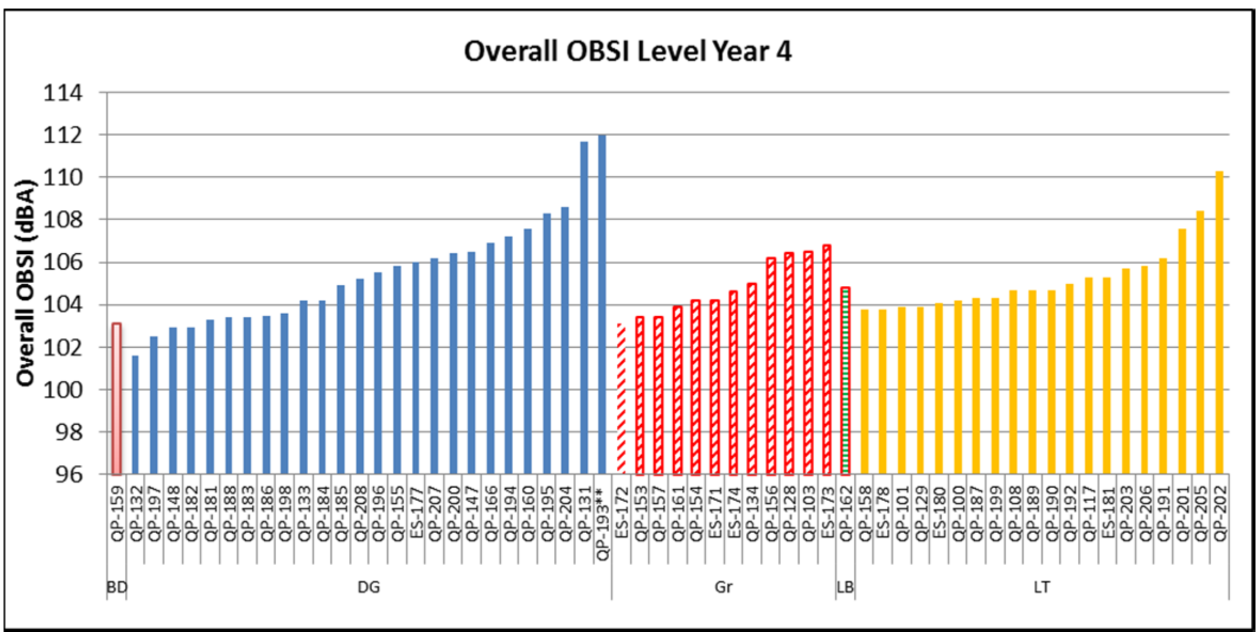

Figure C.4: OBSI for each section measured in Year 4 sorted by texture type and OBSI level.

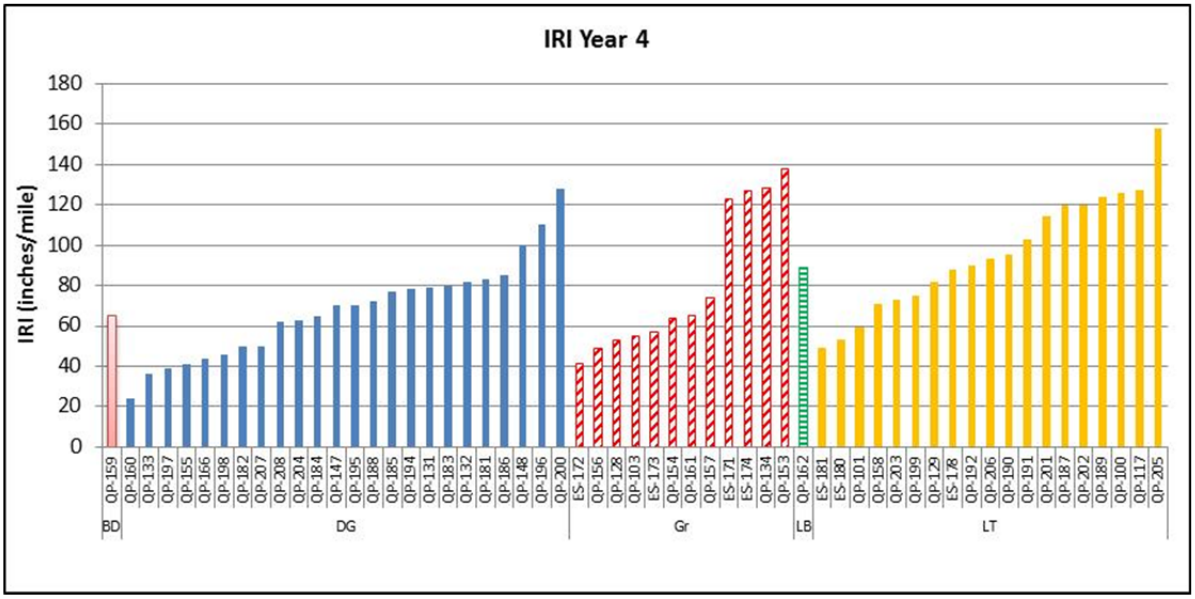

Figure C.5: IRI for each section measured in Year 4 sorted by texture type and IRI level.

APPENDIX D: STATISTICAL ANALYSIS AND MODELING FOR OVERALL OBSI

Statistical analyses and modeling of the overall OBSI were conducted using data from all of the sections included in the fourth-year factorial and considering all the measurements on those sections over the four years.

Appendix D.1: Evaluation of Interactions between Traffic, Rainfall, and Age

In order to simplify the effect of traffic and rainfall on the overall sound intensity of pavement sections, two levels were defined for each variable. Traffic was categorized as *high* if the AADT (two-way) was greater than 32,000 vehicles per day, and traffic with amounts lower than that were categorized as *low*. Rainfall was based on the annual average rainfall in California from 1960 to 1990, with amounts greater than 620 mm (24.4 inches) categorized as *high* and smaller quantities as *low*. The GLM Univariate was employed to model the value of overall sound intensity based on its relationship to the traffic and rainfall categories and texture age. By default, the GLM Univariate procedure produces a model with all factorial interactions, which means that each combination of factor levels can have a different linear effect on the dependent variable. Additionally, factor-covariate interactions may also be specified, if the linear relationship between a covariate and the dependent variable changes for different levels of a factor.

For the purposes of testing hypotheses concerning parameter estimates, the GLM Univariate assumes the following:

- The values of errors are independent of each other and the variables in the model. Good study design generally avoids violation of this assumption.
- The variability of errors is constant across cells. This can be particularly important when there are unequal cell sizes; that is, different numbers of observations across factor-level combinations.
- The errors have a normal distribution with a mean of 0.

Table D.1 shows the results of the analysis for the interaction terms between traffic, rainfall, and texture age. The significance values of the interaction terms are all greater than 0.10, which shows they are not important. Moreover, their partial eta squared term is near 0, showing that they account for a negligible amount of variation compared to the error term. These results mean that homogeneity of the coefficient for the covariate across the levels of the factor can be assumed. The partial eta squared statistic reports the “practical” significance of each term, based upon the ratio of the variation (sum of squares) accounted for by the term, to the sum of the variation accounted for by the term and the variation left to error. Larger values of partial eta squared indicate a greater amount of variation accounted for by the model term, to a maximum of 1.

Table D.1: Results of the GLM Analysis for Interaction Terms

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	112.152[a]	6	18.692	5.883	.000	.229
Intercept	260228.640	1	260228.640	81908.897	.000	.999
Traffic_category	5.813	1	5.813	1.830	.179	.015
TextureAge	6.578	1	6.578	2.070	.153	.017
Rain_category	.338	1	.338	.106	.745	.001
Traffic_category * Rain_category	6.989	1	6.989	2.200	.141	.018
Traffic_category * TextureAge	.038	1	.038	.012	.914	.000
Rain_category * TextureAge	.642	1	.642	.202	.654	.002
Error	378.069	119	3.177			
Total	1376534.532	126				
Corrected Total	490.221	125				

a. R Squared =.229 (Adjusted R Squared =.190)

Table D.2 shows GLM analysis for traffic and rainfall. The descriptive statistics table shows a difference in the mean overall sound intensity for each category. There is a slight difference in the standard deviations, with the high traffic/high rainfall category having a higher standard deviation of 2.09 dBA. In the table showing the results of tests of between-subjects effects, the significance value for the texture age is less than 0.05, indicating that it has a significant effect on overall sound intensity, while the other categories do not appear to be significant. The traffic variable also appears to be significant.

It can be seen in the parameter estimates table that with other variables fixed an increase of one year in the age of the pavement will result in an increase in overall sound intensity of about 0.084 dBA, which means that over about fifteen years the overall OBSI would be expected to increase by about 1.3 dBA on average. The parameter estimates table also indicates that a pavement with low traffic would be expected to have an overall OBSI level that is 0.11 dBA lower than another pavement in the high traffic level category with the same age and same rainfall level.

Table D.2: Results of the GLM Analysis for Each Category

Between-Subjects Factors

		Value Label	N
Traffic Category	1	Low Traffic	67
	2	High Traffic	59
Rain Category	1	Low Rainfall	103
	2	High Rainfall	23

Descriptive Statistics

Dependent Variable:Overall Sound Intensity (dBA)

Traffic Category	Rain Category	Mean	Std. Deviation	N
Low Traffic	Low Rainfall	103.8	1.93	62
	High Rainfall	104.3	1.35	5
High Traffic	Low Rainfall	105.5	1.64	41
	High Rainfall	104.6	2.09	18

Tests of Between-Subjects Effects

Dependent Variable:Overall Sound Intensity (dBA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	111.487[a]	4	27.872	8.905	.000	.227
Intercept	396023.390	1	396023.390	126523.688	.000	.999
TextureAge	37.246	1	37.246	11.900	.001	.090
Traffic_category	11.158	1	11.158	3.565	.061	.029
Rain_category	.002	1	.002	.001	.980	.000
Traffic_category * Rain_category	8.606	1	8.606	2.749	.100	.022
Error	378.734	121	3.130			
Total	1376534.532	126				
Corrected Total	490.221	125				

Parameter Estimates

Dependent Variable:Overall Sound Intensity (dBA)

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Partial Eta Squared
Intercept	104.033	.445	233.785	.000	103.152	104.914	.998
TextureAge	.084	.024	3.450	.001	.036	.133	.090
[Traffic_category=Low]	-.111	.896	-.124	.901	-1.884	1.662	.000
[Traffic_category=High]	0[a]	.	.	.	.	.	.
[Rain_category=Low]	.811	.502	1.614	.109	-.184	1.806	.021
[Rain_category=High]	0[a]	.	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Appendix D.2: Development of Models

Appendix D.2.1: Model with All Textures Combined

Multiple regression analysis was used in order to quantify the effect of each variable on sound intensity.

The first model pooled all the textures together and did not distinguish them in the model. The results of the multiple regression analysis have been tabulated in Table D.3. The ANOVA table reports a significant F statistic, indicating that the whole model is significant at the 0.05 significance level. The significance column of the coefficients table shows that AADTT/Lane, rainfall, and texture age seem to have coefficients that are significant at the 0.95 level in explaining the variation of the overall sound intensity. AADT/Lane was not significant.

A positive value for the coefficient of regression for AADTT/Lane, rainfall, and texture age indicates that the overall sound intensity increases with an increase in truck traffic and rainfall. Higher values of standardized Beta parameters for texture age and AADTT/Lane indicates that overall OBSI is more sensitive to those variables compared to the rainfall.

The values of the partial and part correlations are relatively similar to the zero-order correlation. This means, for example, that much of the variance in overall OBSI that is explained by rainfall cannot be explained by other variables. The tolerance is the percentage of the variance in a given predictor that cannot be explained by the other predictors. Thus, the large tolerances show that 10 percent to 30 percent of the variance in a given predictor can be explained by the other predictors. When the tolerances are close to 0, there is high multi-collinearity and the standard error of the regression coefficients will be inflated. A variance inflation factor (VIF) greater than 2 is usually considered problematic. For the model used in this analysis, all the variance inflation factors in the last column are less than 2.

Table D.3: Results of the Multiple Regression Analysis for All Sections

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.469[a]	.220	.149	1.775807117	.220	3.103	4	44	.025

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	95.003	4	23.751	7.272	.000[a]
	Residual	395.218	121	3.266		
	Total	490.221	125			

Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Err.	Beta			Lower	Upper	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	102.2	.502		203.433	.000	101.2	103.2					
	Rainfall(in.)	.034	.016	.205	2.145	.034	.003	.066	.178	.191	.175	.727	1.375
	Texture Age	.089	.025	.295	3.519	.001	.039	.139	.281	.305	.287	.951	1.052
	AADT/Lane	3.740E-5	.000	.145	1.594	.114	.000	.000	.275	.143	.130	.805	1.242
	AADTT/Lane	.001	.000	.244	2.654	.009	.000	.001	.142	.235	.217	.790	1.265

a. Dependent Variable: Overall Sound Intensity (dBA)

In order to compare the overall sound intensities for different texture types, a Univariate GLM was used with the overall sound intensity as the dependent variable, texture type (shown as "texture") as the categorical variable, and AADT/Lane, AADTT/Lane, rainfall, and texture age as the covariates. All the interactions between the covariates and the texture type were first included in the model. The results for the model are shown in Table D.4. The results indicate that the covariates, texture type, rainfall, average annual daily truck traffic, and texture age are significant factors affecting the overall sound intensity. Among all the interactions, it is evident that texture type and texture age have a significant interaction, while the interactions of texture type with the other covariates are not significant.

The GLM model was run again without the insignificant interaction terms, with results shown in Table D.5. These results indicate that all parameters are significant. However, the adjusted R^2 is only 0.308, indicating that the model does not explain much of the differences in overall OBSI in the data set. The low partial eta square parameters of texture age and rainfall suggest their low importance compared to other variables. Texture type and texture*texture age have the highest influence on the overall sound intensity.

The results of the parameter estimates in Table D.5 indicate that average value of overall sound intensity for the longitudinally tined texture, with a value of 103.8 dBA when all other factors are equal to zero (rainfall, and AADTT/lane, texture age), is the highest. The mean differences for burlap drag, diamond ground, diamond grooved, and longitudinally broomed are -6.2 dBA,-2.1 dBA, -3.4 dBA, and -4.9 dBA respectively. It should be noted that the mean difference for the burlap-drag and longitudinally broomed textures are not statistically significant because there is only one section of each, with four measurements for each section in the experiment design. The coefficient of AADTT/Lane indicates that, with all other factors fixed, the overall sound intensity increases 1.0 dBA for every one-thousand truck increase in a specified lane. With all other factors being fixed, an increase of 10 inches in annual rainfall increases the overall sound intensity by about 0.3 dBA. An increase in pavement age of ten years increases the overall sound intensity of burlap drag, diamond ground, diamond grooved, longitudinal broomed, longitudinally tined, 4.8 dBA, 1.6 dBA, 4.2 dBA, 3.5 dBA, and 0.2 dBA, respectively. Again, as noted the values for the burlap-drag and longitudinal broomed textures are not statistically significant because there is only one section of each in the experiment.

Table D.4: Results of the GLM Model for Effect of Texture Type on Overall Sound Intensity

Tests of Between-Subjects Effects

Dependent Variable:Overall Sound Intensity (dBA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	194.185[a]	18	10.788	3.899	.000	.396
Intercept	75937.780	1	75937.780	27447.117	.000	.996
Texture	32.421	2	16.211	5.859	.004	.099
AADT_Lane	.431	1	.431	.156	.694	.001
AADTT_Lane	24.728	1	24.728	8.938	.003	.077
Rainfall_in	14.447	1	14.447	5.222	.024	.047
TextureAge	11.384	1	11.384	4.115	.045	.037
Texture * TextureAge	55.247	4	13.812	4.992	.001	.157
Texture * AADTT_Lane	7.278	2	3.639	1.315	.273	.024
Texture * AADT_Lane	4.385	2	2.193	.793	.455	.015
Texture * Rainfall_in	7.176	2	3.588	1.297	.278	.024
Error	296.036	107	2.767			
Total	1376534.532	126				
Corrected Total	490.221	125				

a. R Squared =.396 (Adjusted R Squared =.295)

Table D.5: Results of the GLM Model for Effect of Texture Type on Overall Sound Intensity after Removing Insignificant Terms

Tests of Between-Subjects Effects

Dependent Variable:Overall Sound Intensity (dBA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	180.687[a]	11	16.426	6.050	.000	.369
Intercept	18353.833	1	18353.833	6759.635	.000	.983
Texture	71.348	4	17.837	6.569	.000	.187
AADTT_Lane	28.982	1	28.982	10.674	.001	.086
Rainfall_in	16.880	1	16.880	6.217	.014	.052
TextureAge	10.553	1	10.553	3.886	.050	.033
Texture * TextureAge	57.007	4	14.252	5.249	.001	.156
Error	309.534	114	2.715			
Total	1376534.532	126				
Corrected Total	490.221	125				

a. R Squared =.369 (Adjusted R Squared =.308)

Parameter Estimates

Dependent Variable:Overall Sound Intensity (dBA)

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower	95% Confidence Interval Upper	Partial Eta Squared
Intercept	103.795	.586	177.168	.000	102.634	104.955	.996
[Texture=BD]	-6.263	4.479	-1.398	.165	-15.136	2.610	.017
[Texture=DG]	-2.142	.621	-3.450	.001	-3.371	-.912	.095
[Texture=Gr]	-3.423	.762	-4.494	.000	-4.932	-1.914	.151
[Texture=LB]	-4.908	3.654	-1.343	.182	-12.147	2.330	.016
[Texture=LT]	0[a]	.	.	.	.	.	.
AADTT_Lane	.001	.000	3.267	.001	.000	.001	.086
Rainfall_in	.034	.014	2.493	.014	.007	.061	.052
TextureAge	.025	.028	.893	.374	-.030	.079	.007
[Texture=BD] * TextureAge	.478	.609	.786	.434	-.728	1.684	.005
[Texture=DG] * TextureAge	.162	.062	2.631	.010	.040	.284	.057
[Texture=Gr] * TextureAge	.422	.108	3.908	.000	.208	.635	.118
[Texture=LB] * TextureAge	.348	.470	.740	.461	-.584	1.279	.005
[Texture=LT] * TextureAge	0[a]	.	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Estimates Marginal Means

Dependent Variable:Overall Sound Intensity (dBA)

Surface Texture	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
BD	102.788[a]	.894	101.016	104.559
DG	104.463[a]	.239	103.989	104.938
Gr	105.188[a]	.367	104.461	105.915
LB	103.133[a]	.839	101.470	104.795
LT	105.350[a]	.297	104.763	105.938

a. Covariates appearing in the model are evaluated at the following values: Rainfall (in.) = 14.036984, Texture Age = 7.736364, AADTT/Lane = 1013.411442.

Appendix D.2.2: Models for Each Texture Type (DG, Gr, LT)

In order to further study all the factors affecting noise within each texture type, the same analysis was performed for each texture type. Since there were not many pavement sections with the burlap-drag and longitudinally broomed texture types, the analysis was performed only for the diamond-ground, diamond-grooved, and longitudinally tined texture types, which are the predominant ones used in California. The results are tabulated in Table D.6 to Table D.8.

Results of the models indicate the following:

- The linear model with the explanatory variables of rainfall, texture age, AADT/Lane, and AADTT/Lane is very poor in explaining overall OBSI for the diamond-ground and longitudinally tined textures, with adjusted R^2 of 0.149 and 0.010, respectively. For the diamond-grooved texture, the model is better able to explain overall OBSI, as indicated by an adjusted R^2 of 0.573.
- Texture age, rainfall, and AADTT/Lane are significant factors at the 95 percent confidence level affecting the overall sound intensity of the diamond-grooved texture, and the model predicts an increase in overall OBSI with an increase in texture age, rainfall, and AADTT/Lane, as expected. For the model for the diamond-ground texture, the only significant variable is texture age, and for the longitudinally tined texture model there are no significant variables at the 95 percent confidence level.

Table D.6: Results of the Multiple Regression Analysis for Diamond-Ground Sections

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.469[a]	.220	.149	1.775807117	.220	3.103	4	44	.025

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	39.147	4	9.787	3.103	.025[a]
	Residual	138.754	44	3.153		
	Total	177.900	48			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower	Upper	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	102.017	1.069		95.414	.000	99.862	104.172					
	Rainfall(in.)	.036	.032	.213	1.129	.265	-.028	.100	.147	.168	.150	.496	2.017
	Texture Age	.185	.068	.417	2.722	.009	.048	.322	.425	.380	.362	.756	1.322
	AADT/Lane	1.071E-5	.000	.041	.244	.808	.000	.000	.292	.037	.033	.615	1.626
	AADTT/Lane	.000	.001	.080	.456	.650	-.001	.002	-.004	.069	.061	.582	1.719

a. Dependent Variable: Overall Sound Intensity (dBA)

Table D.7: Results of the Multiple Regression Analysis for Diamond-Grooved Sections

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.789[a]	.623	.573	1.229559472	.623	12.384	4	30	.000

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	74.889	4	18.722	12.384	.000[a]
	Residual	45.354	30	1.512		
	Total	120.244	34			

Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower	Upper	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	98.621	.992		99.395	.000	96.595	100.648					
	Rainfall(in.)	.123	.050	.571	2.491	.018	.022	.225	.083	.414	.279	.239	4.184
	Texture Age	.512	.089	.737	5.743	.000	.330	.694	.639	.724	.644	.762	1.312
	AADT/Lane	-6.721E-5	.000	-.328	-1.526	.138	.000	.000	.350	-.268	-.171	.273	3.667
	AADTT/Lane	.002	.000	.664	3.837	.001	.001	.003	.329	.574	.430	.420	2.380

a. Dependent Variable: Overall Sound Intensity (dBA)

Table D.8: Results of the Multiple Regression Analysis for Longitudinally Tined Sections

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.361[a]	.130	.010	1.953152264	.130	1.087	4	29	.381

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	16.581	4	4.145	1.087	.381[a]
	Residual	110.629	29	3.815		
	Total	127.210	33			

Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower	Upper	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	103.846	.889		116.815	.000	102.028	105.664					
	Rainfall(in.)	.014	.023	.108	.618	.542	-.033	.061	.110	.114	.107	.980	1.021
	Texture Age	.026	.033	.138	.772	.446	-.043	.094	.058	.142	.134	.935	1.069
	AADT/Lane	2.273E-5	.000	.076	.423	.675	.000	.000	.158	.078	.073	.934	1.071
	AADTT/Lane	.001	.001	.325	1.769	.087	.000	.002	.303	.312	.306	.890	1.123

a. Dependent Variable: Overall Sound Intensity (dBA)

APPENDIX E: INVESTIGATION OF ROAD SURFACE CHARACTERIZATION PARAMETERS AND OVERALL OBSI

The texture statistical parameters investigated for correlation with OBSI are the following:

Surface line length. This is calculated by summing the lengths of the straight segments joining the data values in each transverse row of surface elevations and is the linear equivalent of the surface area.

Tangent of β_0. This is a characteristic of the steepness of local slopes, and is closely related to the behavior of autocorrelation and height-height correlation functions at zero. For discrete values it is calculated as follows:

$$\tan^2 \beta_0 = \frac{1}{(N-1)h^2} \sum_{i=1}^{N=1} (z_i - z_{i-1})^2$$

where N is the total number of points on the line, h is the average distance between points i-1 and I, and z_{i-1} and z_i are the elevation of two consecutive points.

In the following formulas it is assumed that the mean value of r_j is zero, i.e., it holds that

$$r_j = z_j - \bar{z}$$

Roughness Average (R_a). This the arithmetical mean deviation, which is the average deviation of all points in the roughness profile from a mean line over the evaluation length:

$$R_a = \frac{1}{N} \sum_{j=1}^{N} |r_j|$$

Maximum Height of the Profile (R_t). This the maximum peak-to-peak-valley height, which is the absolute value between the highest and lowest peaks:

$$R_t = |\min r_j, \quad 1 \le J \le N| + |\max r_j, 1 \le J \le N|$$

Ten-point height (R_z). This the average absolute value of the five highest peaks and the five lowest valleys over the evaluation length.

Root Mean Square Roughness. This the average of the measured height deviations taken within the evaluation length and measured from the mean line.

$$RMS = \sqrt{\frac{1}{N}\sum_{j=1}^{N} r^2{}_j}$$

Standard error of surface parameters. The standard error of all the above texture parameters was also calculated and tabulated as a measure of the variability of the parameter potentially being an explanatory variable.

Skewness. A parameter that describes the shape of the Amplitude Distribution Function (ADF). Skewness is a simple measure of the asymmetry of the ADF, or, equivalently, it measures the symmetry of the variation of a profile about its mean line.

Kurtosis. This relates to the uniformity of the ADF or, equivalently, to the spikiness of the profile.

Values for all the above texture parameters for the sections on which the surface texture was measured using the LTS are shown in Table E.1.

Diamond-grooved and longitudinally tined textures seem to have higher values for all of the parameters described above compared to other texture types. The relationships between each of the above parameters and the overall sound intensity were studied using simple linear regression, as shown in Appendix F.

The results indicate that there is a strong relationship between overall sound intensity and skewness, standard error of $\tan\beta_0$, and standard error of R_t. The magnitude of overall sound intensity increases with an increase in the absolute value of skewness, standard error of $\tan\beta_0$, and standard error of R_t. No strong relationship was found between the overall sound intensity and macrotexture parameters such as MPD, MTD, and outflow time.

In order to study what component of the noise is more affected by these texture parameters, the correlation coefficients for the relationship between one-third octave band frequencies and the above texture parameters were calculated and are shown in Table E.2.

The results shown in Table E.2 indicate that the texture parameters that had a strong relationship with overall sound intensity, i.e., skewness, standard error of $\tan\beta_0$, and standard error of R_t, also had a strong correlation with noise levels for frequencies less than 1,600 Hz. Among the typically measured macrotexture parameters, MPD was found to be best correlated with low frequencies up to 1,250 Hz, as is also the case for asphalt pavements. No strong correlation was found between any of the calculated texture parameters and high frequency noise levels. The fairly strong correlation between high frequency noise levels and the outflow time is expected as it is a measure of the ability of fluid (air or water) to escape from under the tire. Air and water permeability have been shown to similarly correlate with high frequency noise for asphalt pavements. These results indicate that the outflow meter can potentially be used as a tool to assess sound intensity at high frequencies.

Table E.1: Texture Parameters Calculated for Test Sections with LTS Measurements

Tex	QP	Surface Length (0.1m)	L/w	Length, std.err (0.001m)	$Tan(\beta_0)$* 10^{-2}	$Tan(\beta_0)$, std.err *10^{-3}	R_a (0.1mm)	R_a, std.err (0.01mm)	RMS (0.1mm)	RMS, std.err (0.01mm)	R_z (mm)	R_z, std.err (0.1mm)	R_t (mm)	R_t, std.err (0.1mm)	Skewness	Kurtosis
BD	QP-159	1.161	1.161	2.666	1.022	4.438	2.169	9.008	2.575	8.943	0.656	1.530	1.362	2.689	-0.198	2.982
DG	QP-155	1.193	1.193	2.480	1.163	3.084	2.460	1.553	3.005	2.013	1.044	1.257	1.597	1.151	-0.165	2.707
	QP-160	1.174	1.174	1.822	1.211	3.966	1.728	1.226	2.158	1.369	0.869	0.413	1.240	0.887	-0.408	0.215
	QP-166	1.213	1.213	1.779	1.184	3.218	2.788	1.705	3.345	2.050	1.249	1.197	1.702	1.849	-0.094	2.430
Gr	QP-154	1.302	1.302	2.262	2.954	4.482	9.056	6.443	11.000	5.697	3.233	1.568	3.799	2.301	-1.189	2.851
	QP-156	1.500	1.500	2.628	6.000	12.000	13.530	10.610	15.340	10.200	4.274	2.300	5.005	5.820	-2.620	1.800
	QP-157	1.673	1.673	2.937	8.865	6.051	15.570	21.340	17.800	13.180	4.784	1.241	5.847	2.116	-0.690	2.048
	QP-161	1.737	1.737	2.440	13.200	8.678	16.330	55.650	22.010	46.630	7.242	0.791	7.726	4.062	-2.025	6.353
LB	QP-162	1.165	1.165	0.999	0.892	2.453	1.504	5.853	1.818	6.487	0.516	0.611	0.920	2.025	-0.201	2.705
LT	QP-127	0.828	1.115	1.014	4.886	3.637	3.539	2.763	4.195	2.848	1.314	1.251	1.818	2.894	-0.356	2.910
	QP-158	1.239	1.239	2.883	1.861	9.160	6.833	11.310	9.067	13.400	2.561	2.508	4.112	5.353	-2.066	4.626
	QP-187	0.798	1.108	1.008	5.056	5.084	7.516	6.896	9.263	9.388	2.331	2.442	3.479	3.542	-1.099	3.106
	QP-199	0.719	1.065	0.750	3.618	4.101	4.688	5.322	6.069	7.958	1.511	1.969	2.409	3.486	-1.449	3.956

Table E.2: Coefficient of Correlation between Different Texture Parameters and Sound Intensities at One-Third Octave Bands

Freq (Hz)	Outflow	MTD	MPD	Surf. Length	L/w	Length, std.err	$Tan(\beta_0)$	$Tan(\beta_0)$, std.err	R_a	R_a, std.err	RMS	RMS, std.err	R_z	R_z, std.err	R_t	R_t, std.err	Skew	Kurt
400 Hz	-0.25	0.40	0.60	-0.07	0.13	-0.15	0.34	0.64	0.41	0.15	0.39	0.23	0.32	0.64	0.40	0.80	-0.65	0.18
500 Hz	-0.31	0.45	0.63	-0.04	0.16	-0.08	0.35	0.71	0.44	0.16	0.43	0.23	0.35	0.68	0.43	0.89	-0.74	0.24
630 Hz	-0.55	0.68	0.72	0.38	0.51	0.29	0.50	0.89	0.69	0.34	0.67	0.36	0.62	0.51	0.67	0.76	-0.81	0.07
800 Hz	-0.46	0.57	0.66	0.20	0.33	0.20	0.38	0.87	0.56	0.21	0.54	0.26	0.49	0.58	0.54	0.82	-0.83	0.04
1,000 Hz	-0.75	0.81	0.74	0.58	0.72	0.49	0.66	0.88	0.83	0.52	0.82	0.51	0.81	0.33	0.83	0.66	-0.85	0.24
1,250 Hz	-0.55	0.68	0.67	0.48	0.56	0.41	0.45	0.92	0.70	0.34	0.68	0.36	0.64	0.52	0.69	0.80	-0.84	0.14
1,600 Hz	0.44	-0.49	-0.39	-0.05	-0.15	0.01	-0.21	0.14	-0.23	0.06	-0.19	0.13	-0.16	0.00	-0.14	0.36	-0.18	0.38
2,000 Hz	0.50	-0.37	-0.38	0.32	0.17	0.26	-0.03	0.12	-0.03	0.32	0.01	0.33	0.06	-0.28	0.05	0.16	-0.10	0.39
2,500 Hz	0.58	-0.33	-0.33	0.27	0.15	0.19	-0.02	0.15	-0.03	0.29	0.00	0.31	0.03	-0.24	0.02	0.22	-0.11	0.33
3,150 Hz	0.16	0.33	0.02	0.77	0.66	0.54	0.33	0.37	0.46	0.57	0.46	0.51	0.49	-0.31	0.45	0.18	-0.26	0.24
4,000 Hz	0.42	-0.03	-0.24	0.62	0.43	0.48	0.02	0.20	0.19	0.30	0.18	0.25	0.19	-0.32	0.17	0.06	-0.08	0.08
5,000 Hz	0.76	-0.78	-0.75	0.11	-0.18	0.15	-0.55	-0.19	-0.47	-0.23	-0.48	-0.23	-0.46	-0.36	-0.47	-0.19	0.32	-0.19

Note: Lightly shaded cells indicate very strong correlation (>0.8) and darkly shaded cells indicate a strong (>0.6) correlation.

APPENDIX F: PLOTS OF ROAD SURFACE CHARACTERIZATION PARAMETERS AND OVERALL OBSI

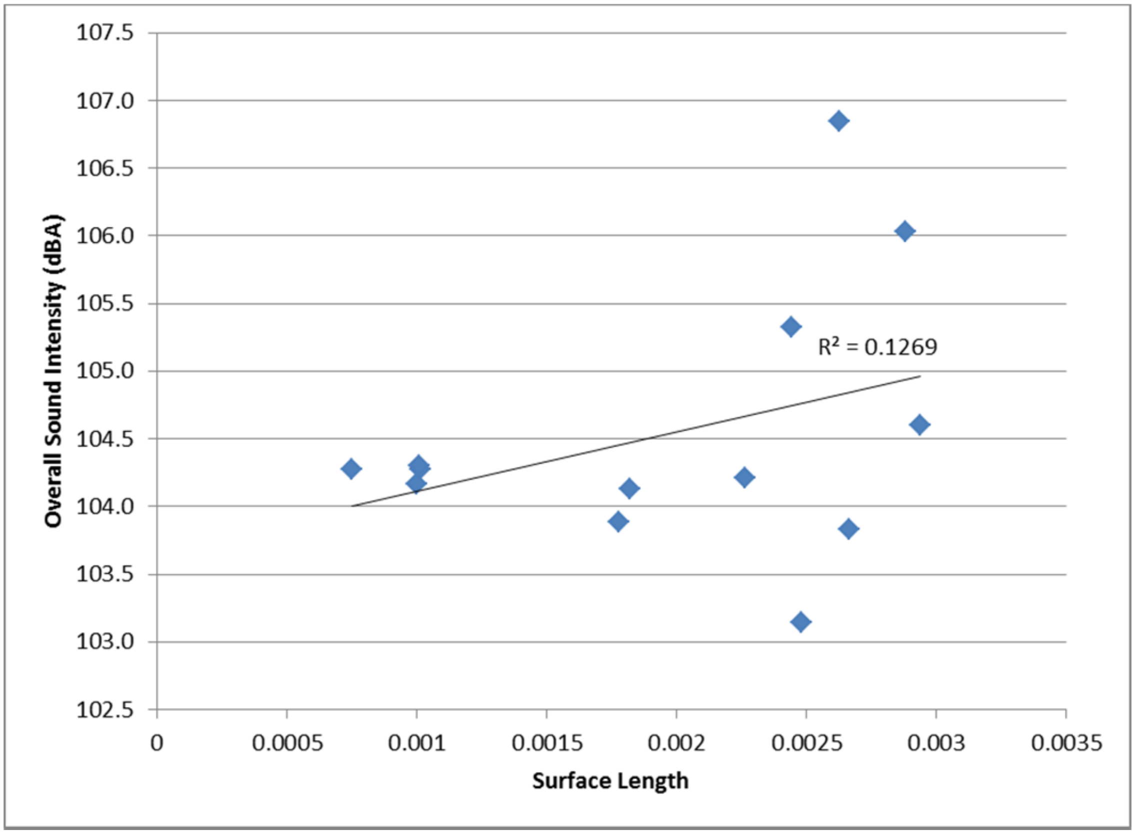

Figure F.1: Relationship between overall sound intensity and surface length.

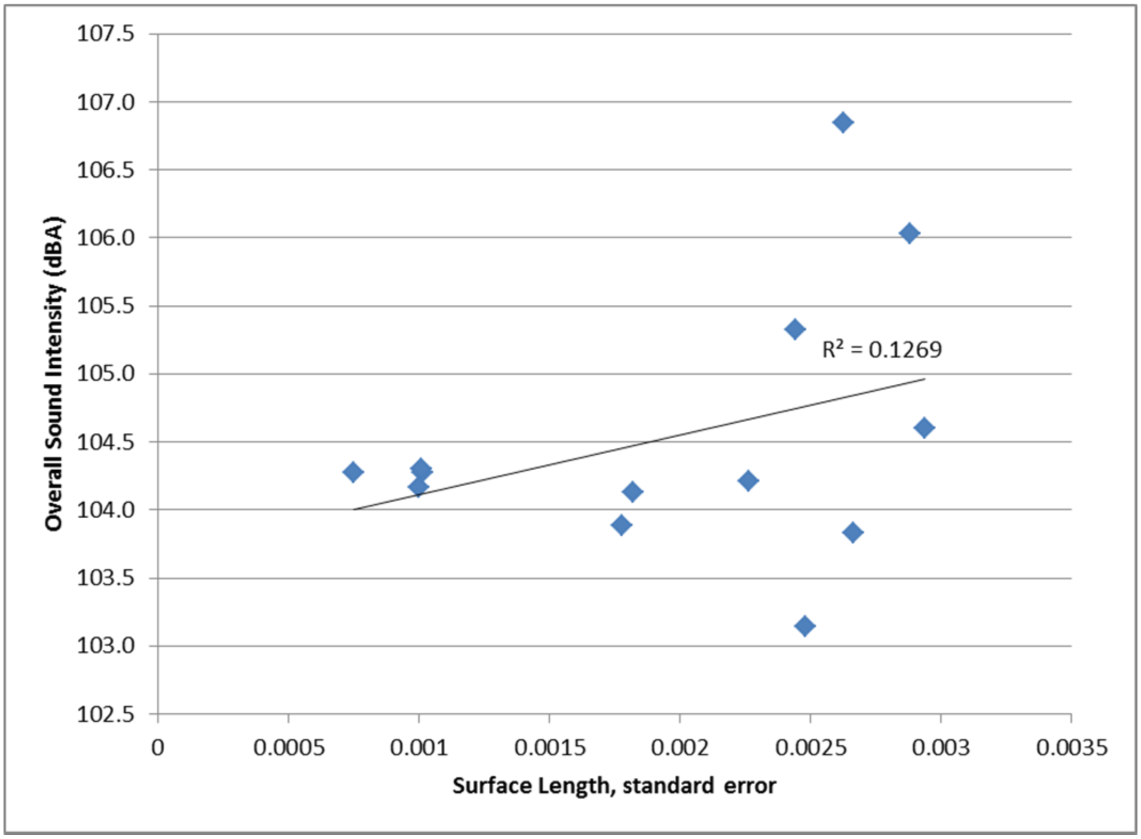

Figure F.2: Relationship between overall sound intensity and surface length standard error.

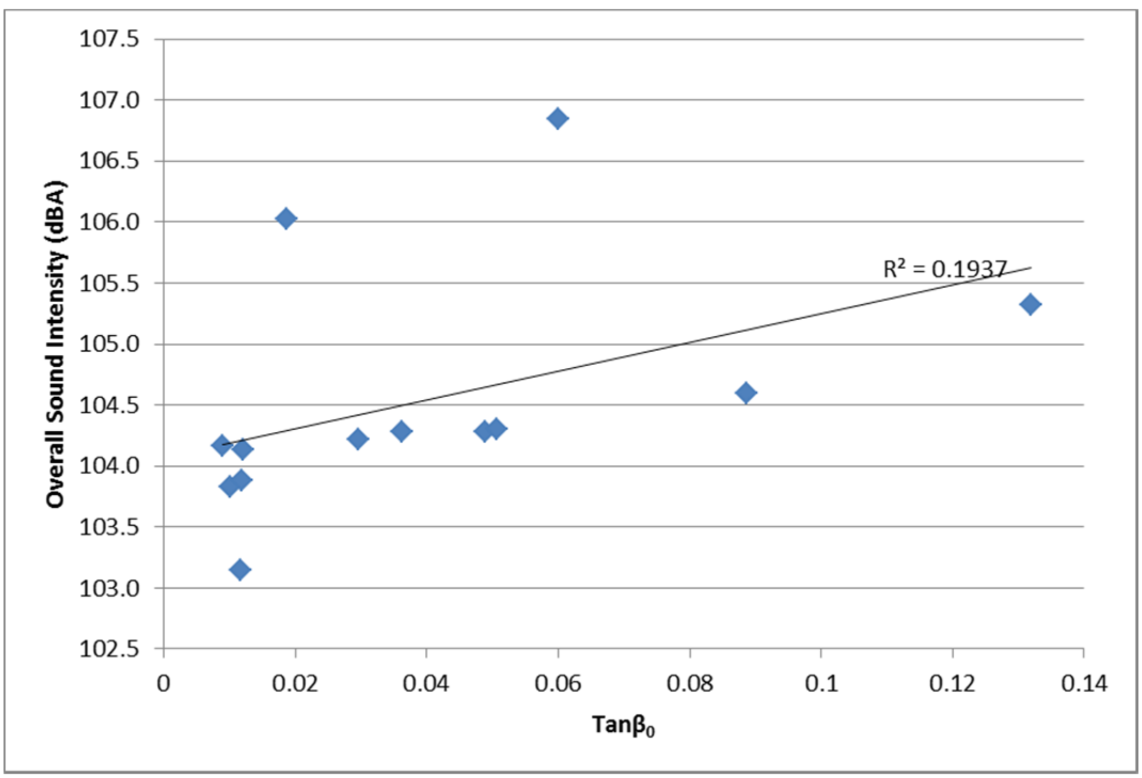

Figure F.3: Relationship between overall sound intensity and tanβ_0.

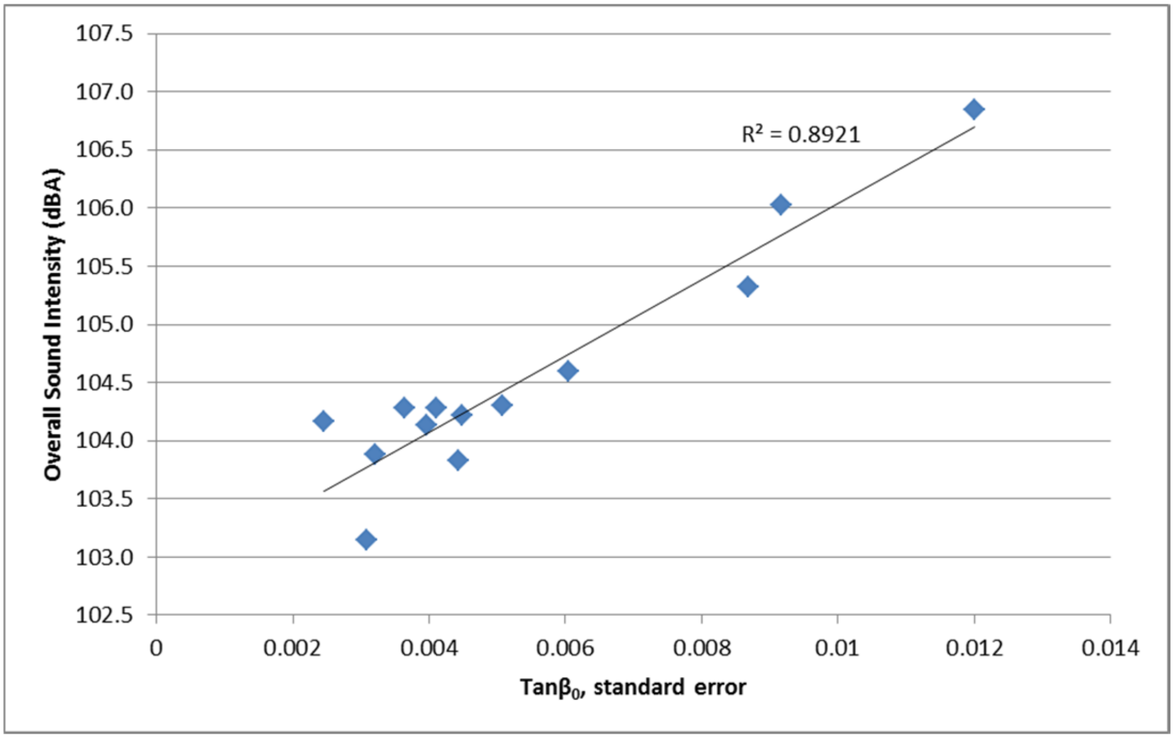

Figure F.4: Relationship between overall sound intensity and tanβ_0 standard error.

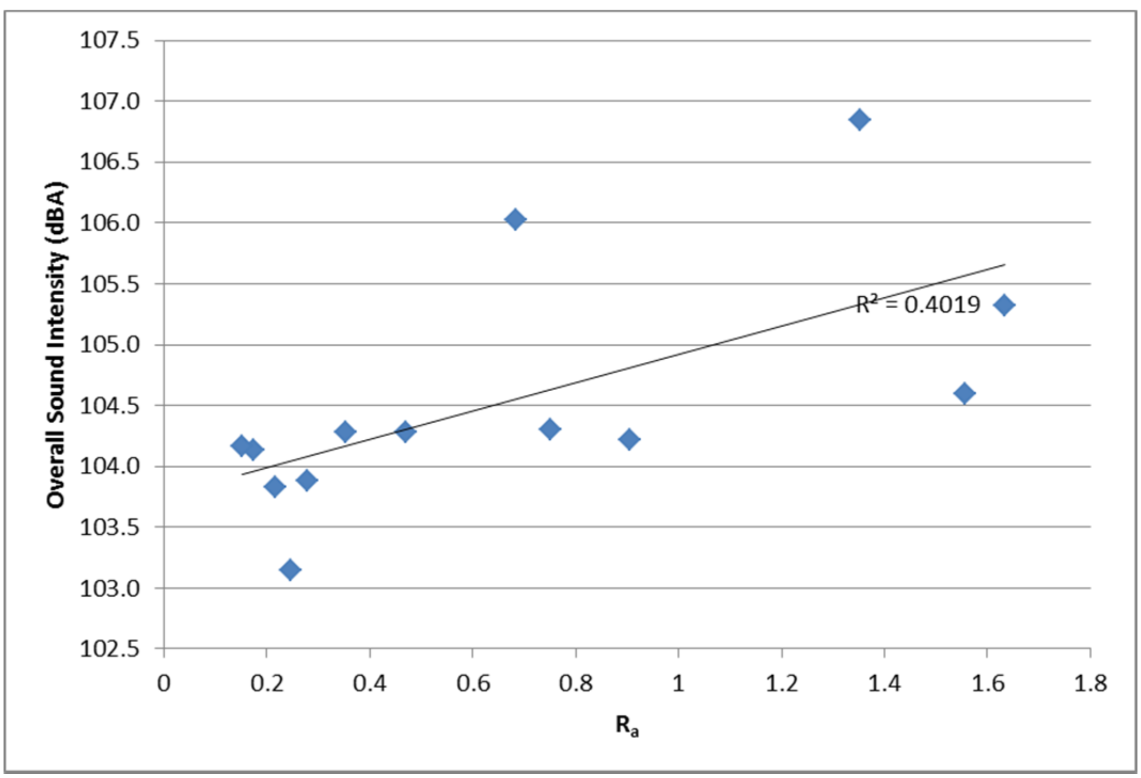

Figure F.5: Relationship between overall sound intensity and R_a.

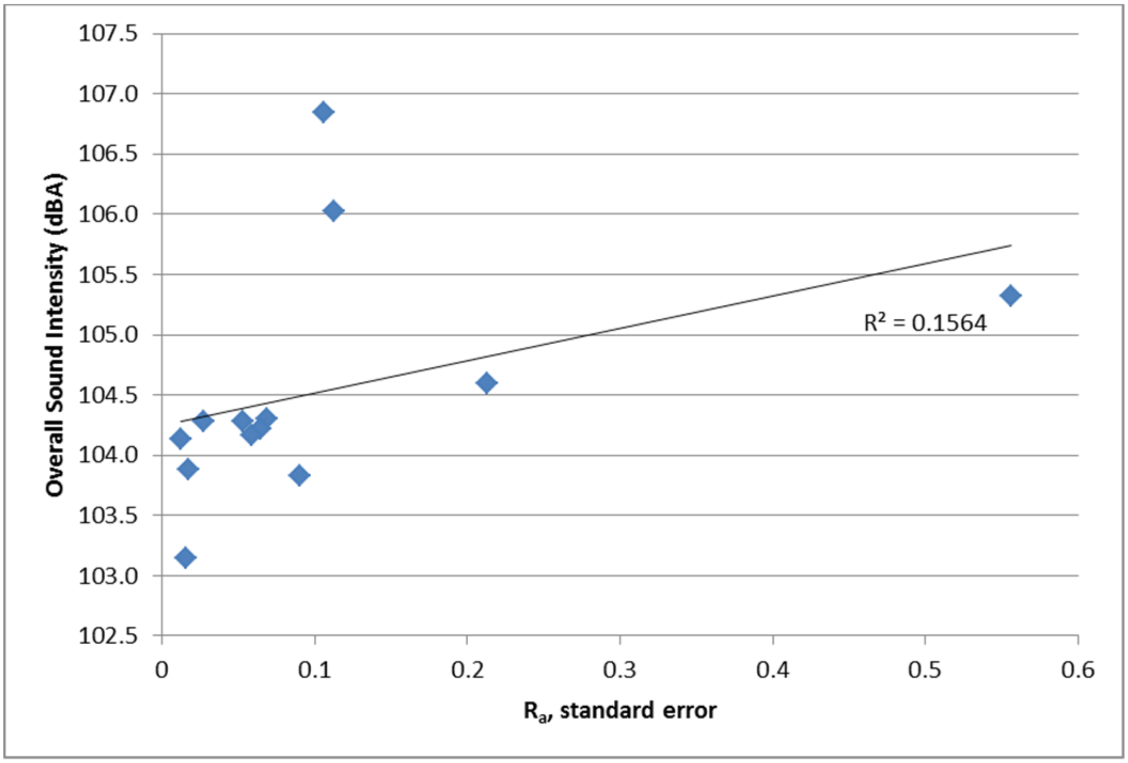

Figure F.6: Relationship between overall sound intensity and R_a standard error.

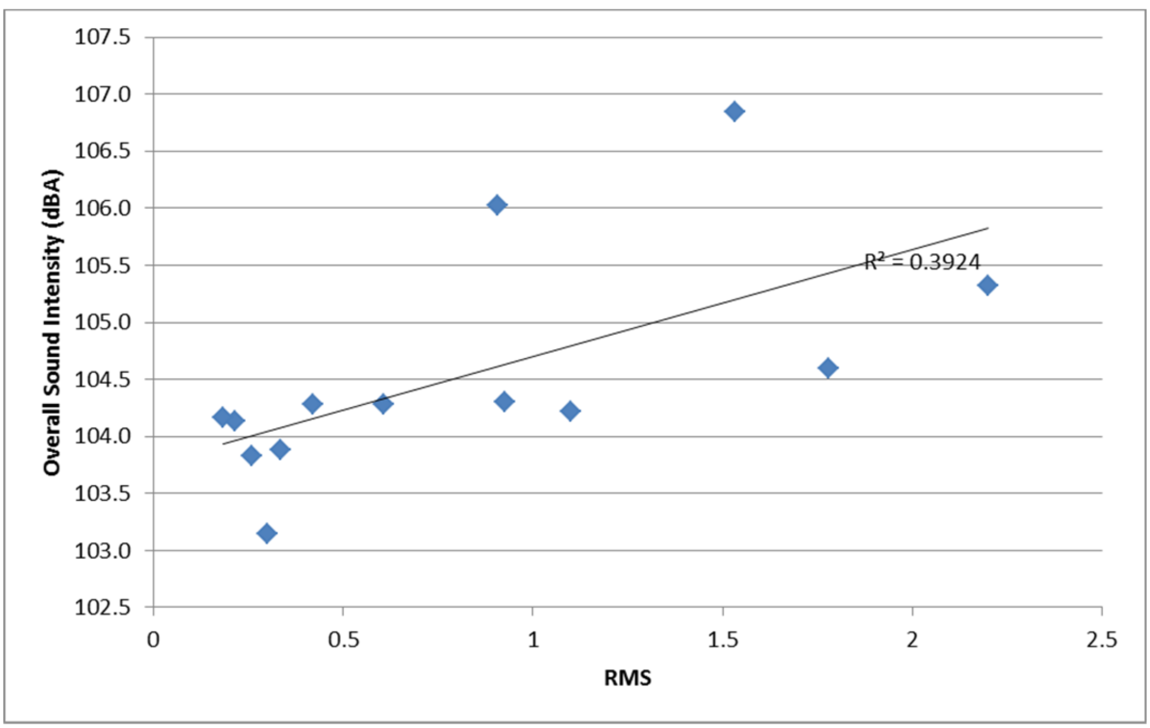

Figure F.7: Relationship between overall sound intensity and RMS.

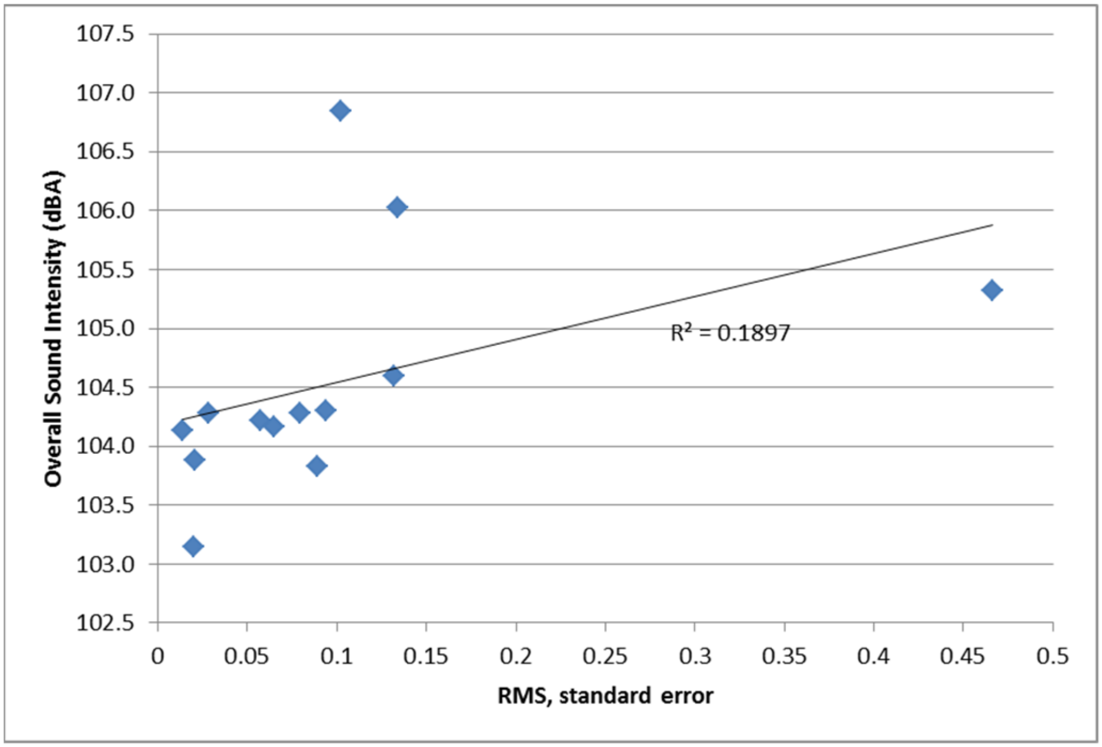

Figure F.8: Relationship between overall sound intensity and RMS standard error.

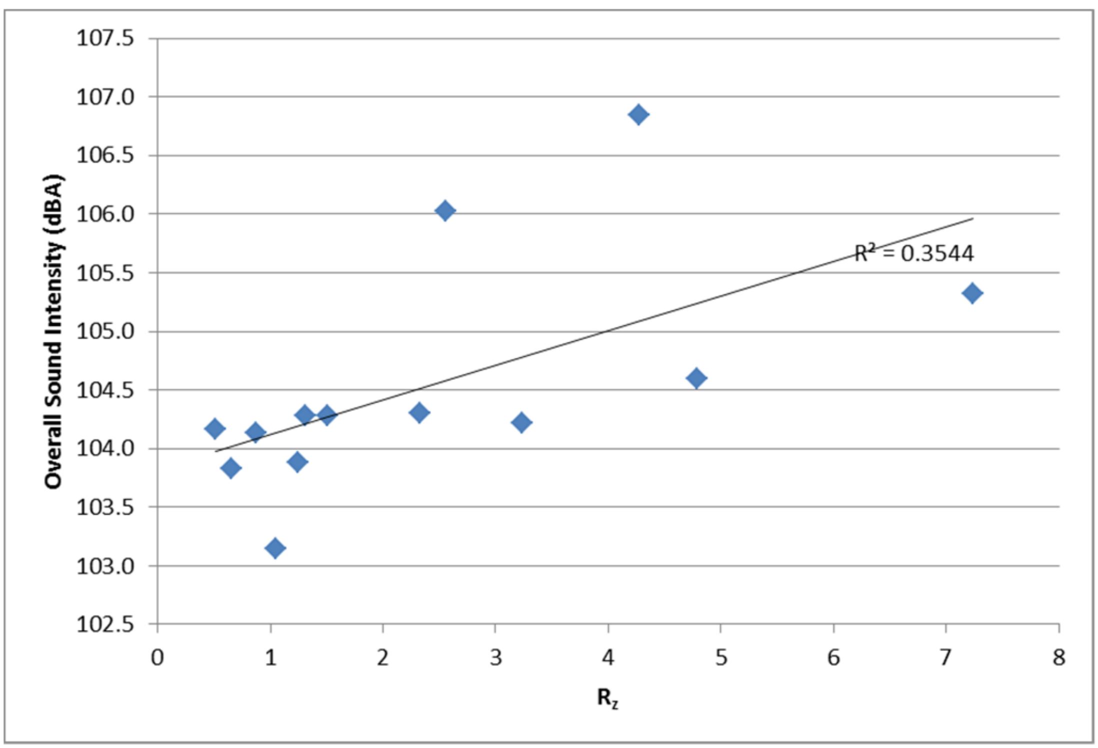

Figure F.9: Relationship between overall sound intensity and R_z.

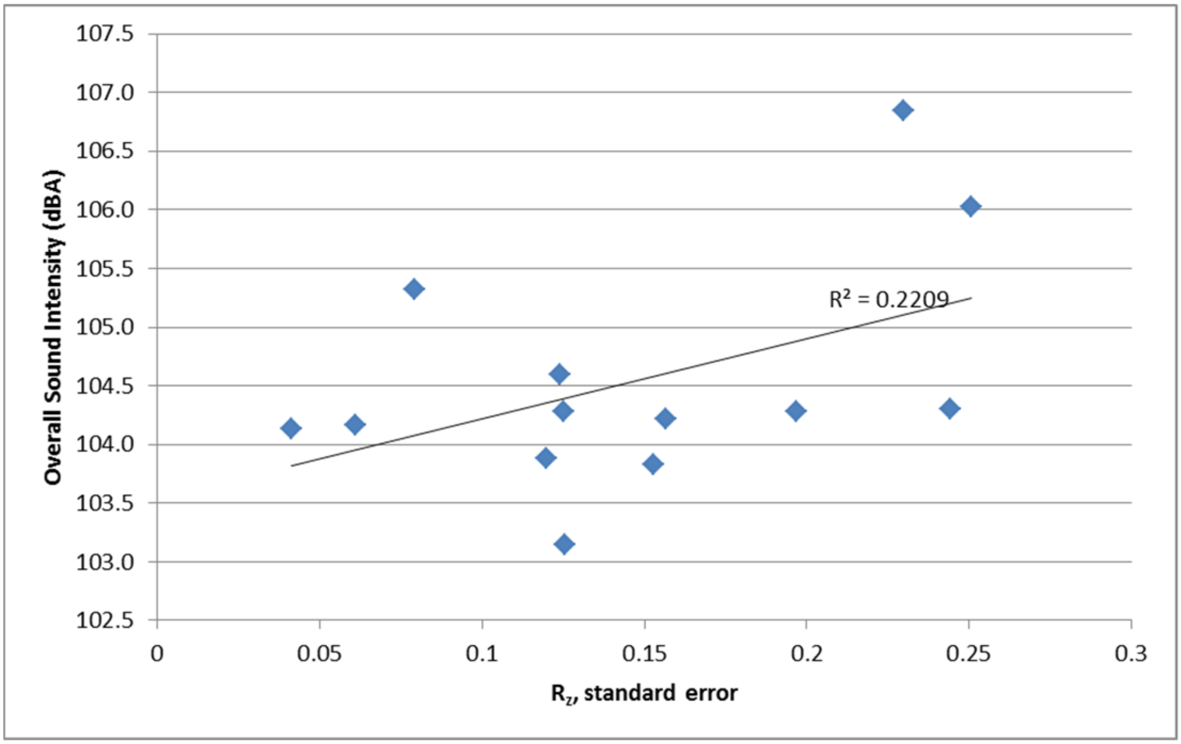

Figure F.10: Relationship between overall sound intensity and R_z standard error.

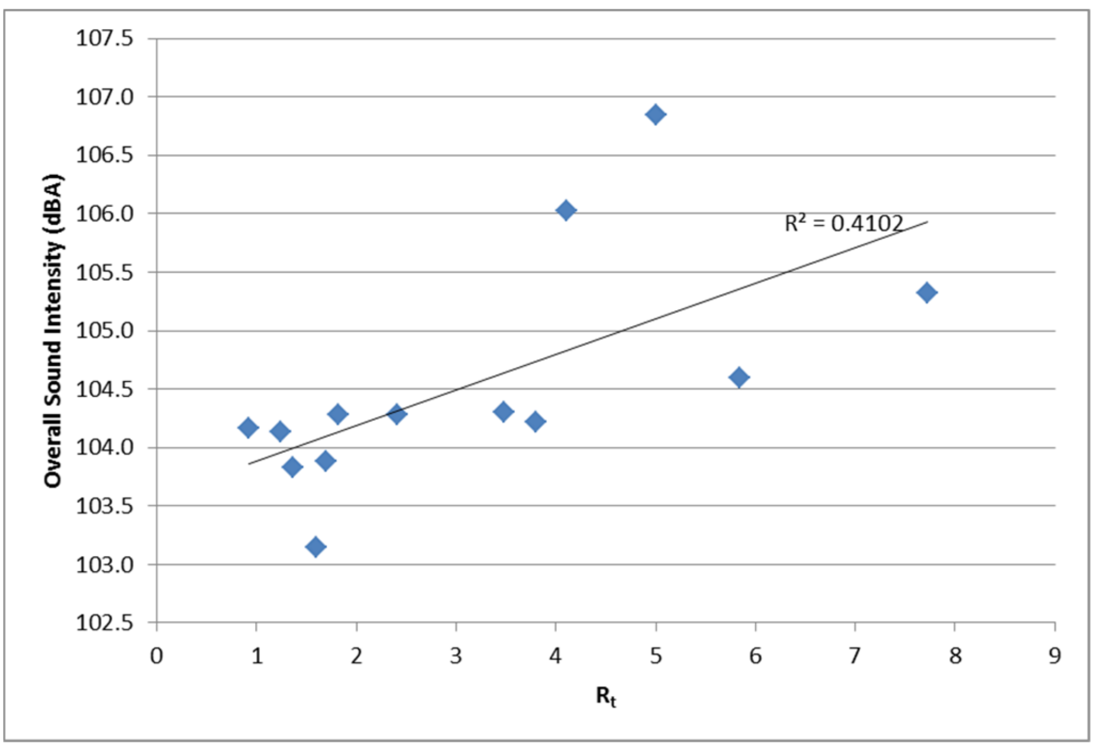

Figure F.11: Relationship between overall sound intensity and R_t.

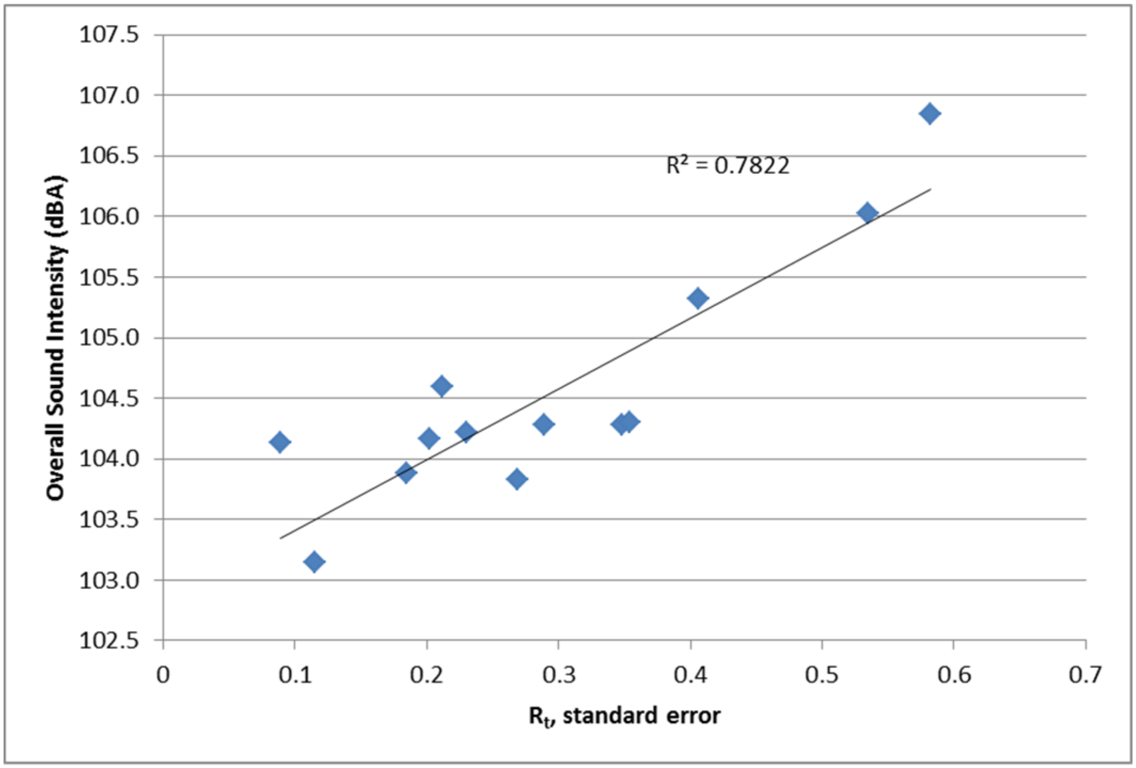

Figure F.12: Relationship between overall sound intensity and R_t standard error.

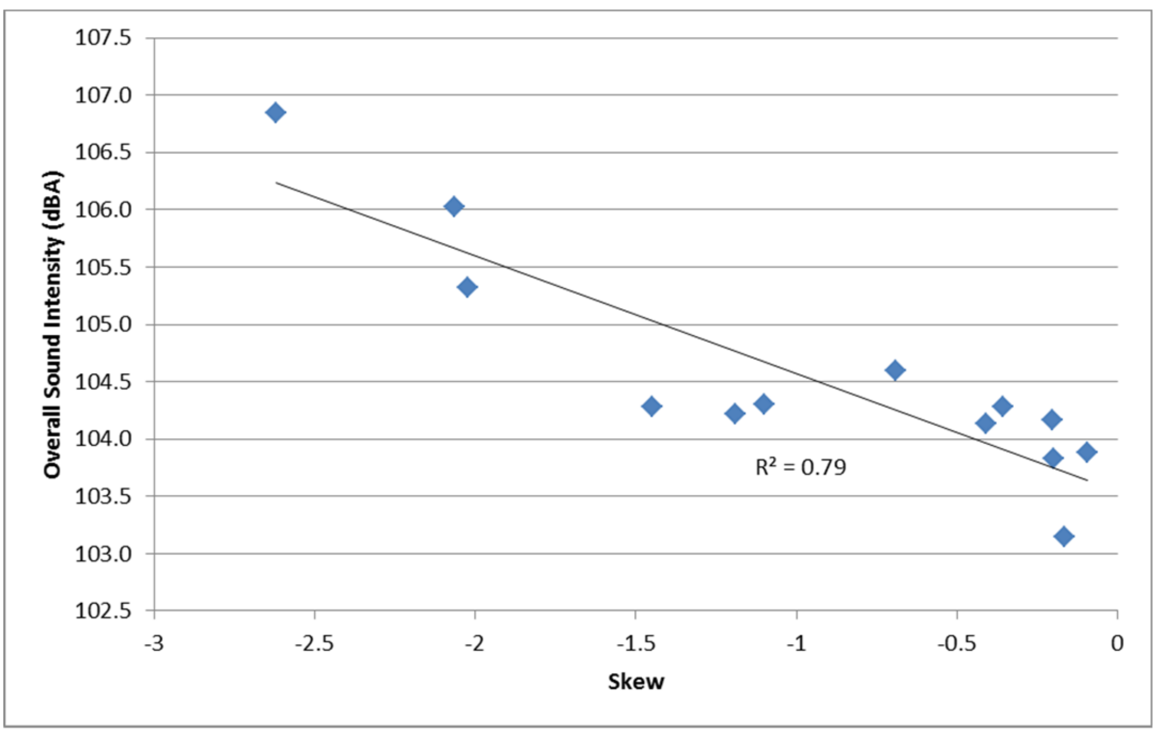

Figure F.13: Relationship between overall sound intensity and skewness.

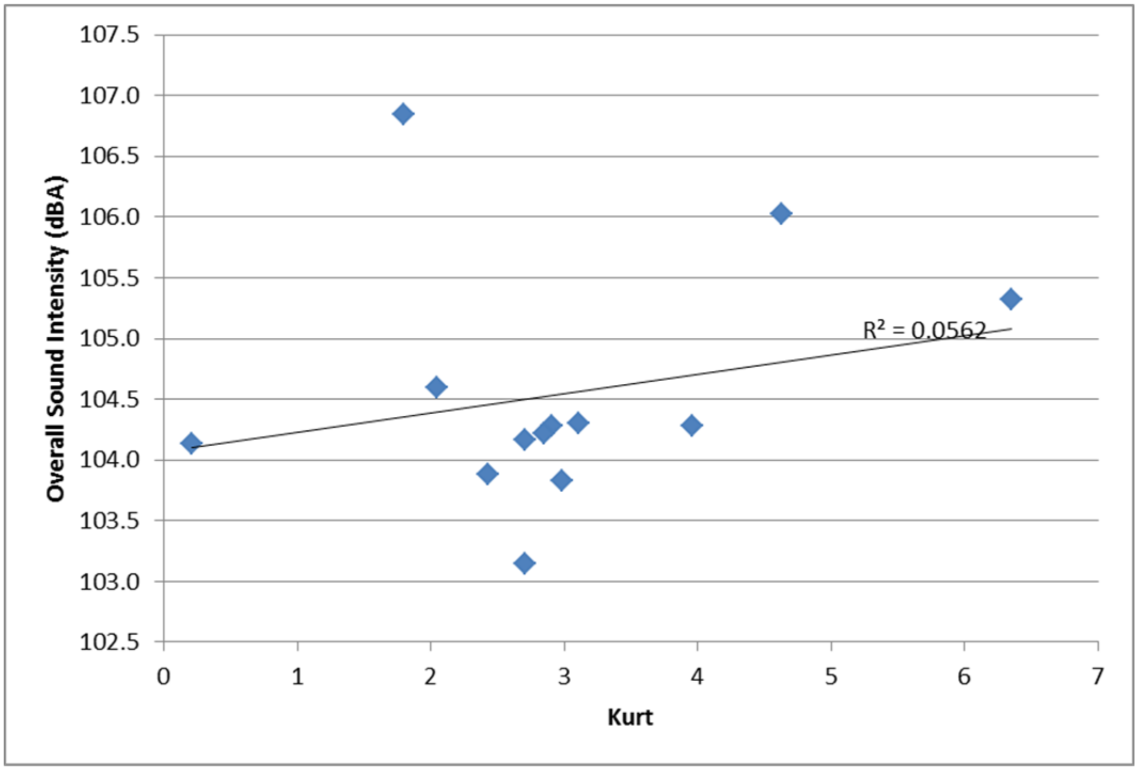

Figure F.14: Relationship between overall sound intensity and kurtosis.

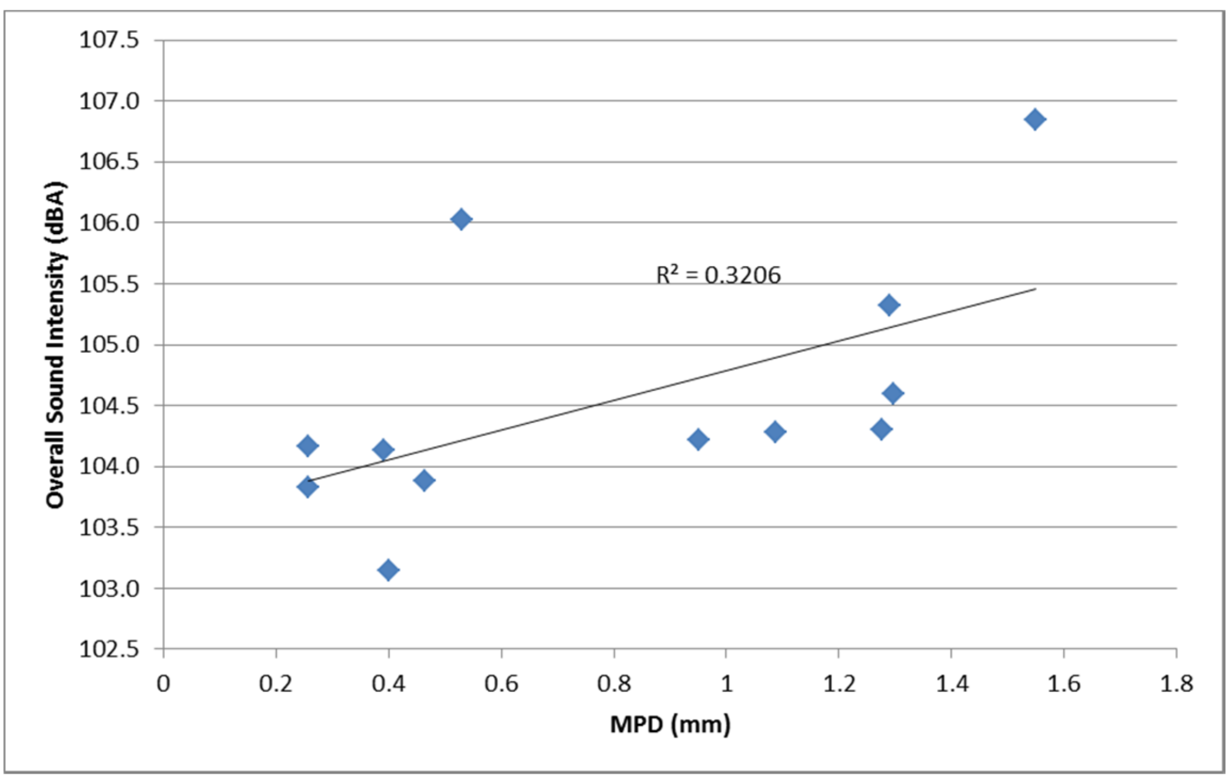

Figure F.15: Relationship between overall sound intensity and MPD.

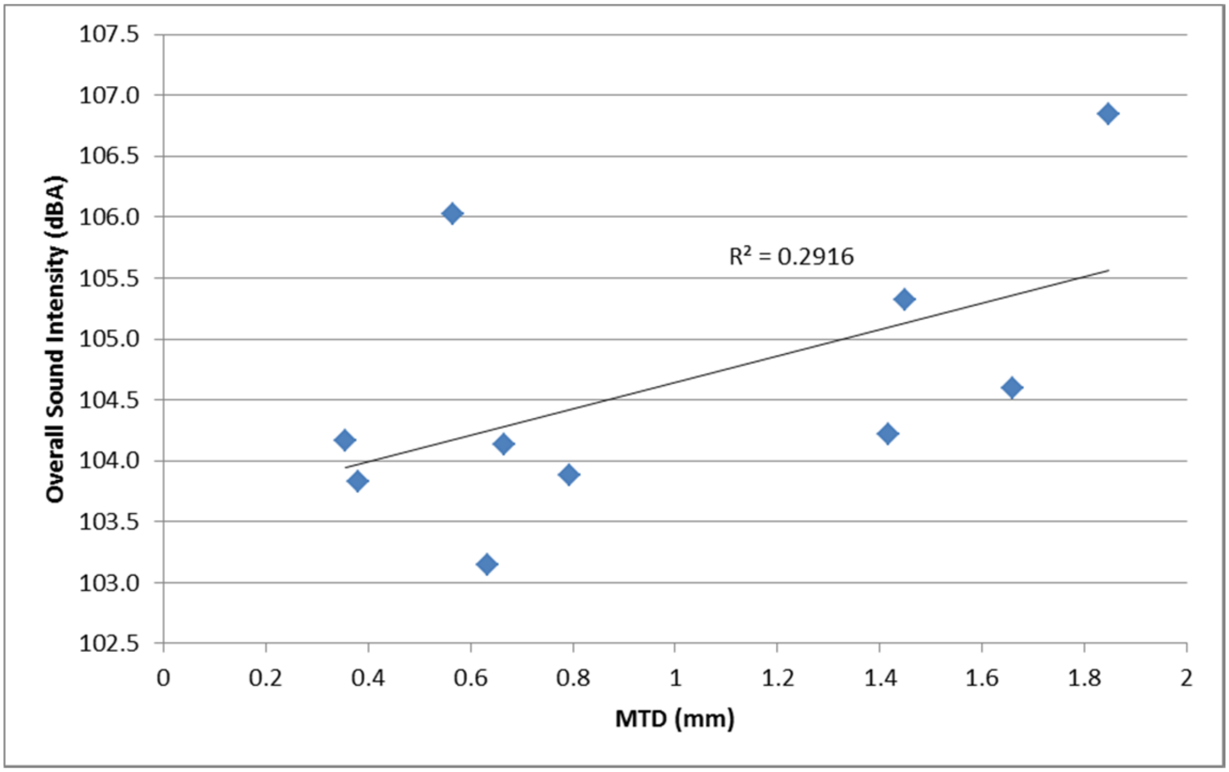

Figure F.16: Relationship between overall sound intensity and MTD.

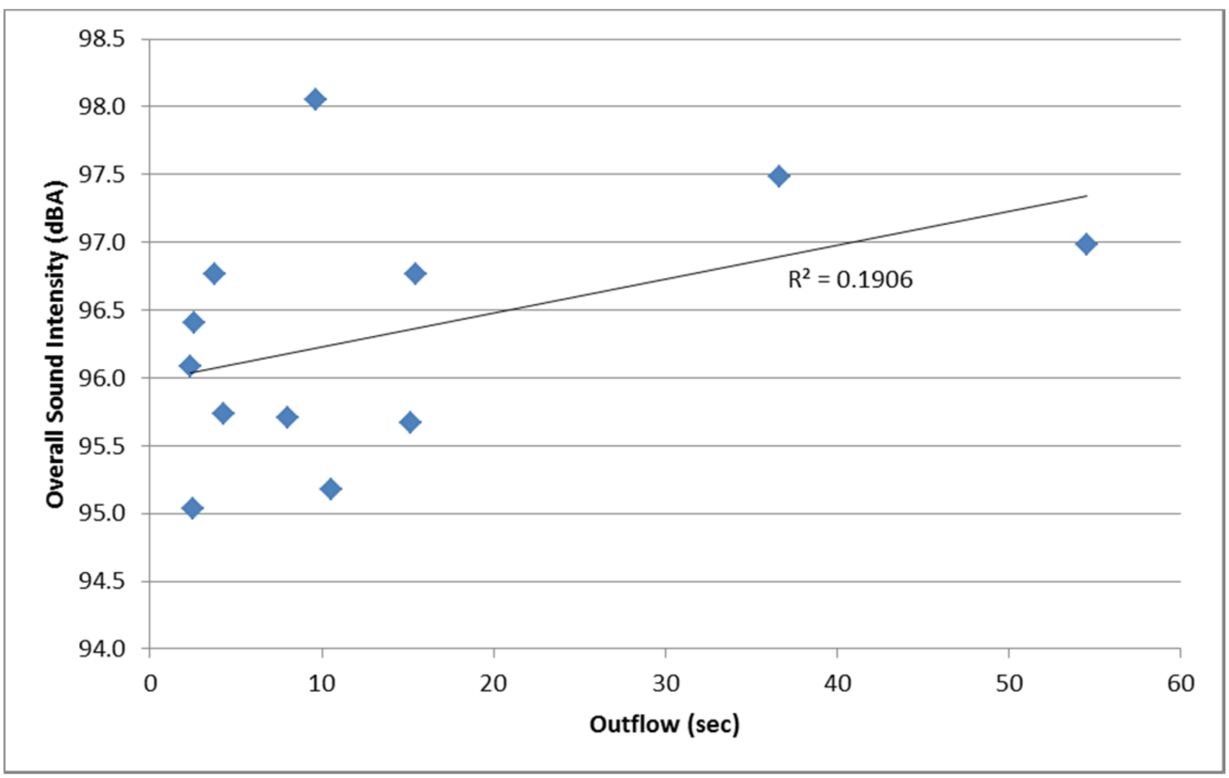

Figure F.17: Relationship between overall sound intensity and outflow time.