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Concrete Pavement Tire Noise: Third-Year Results

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Abstract: This research report presents the results of tire/pavement noise measurements performed on concrete pavements as a part of the California Department of Transportation (Caltrans) Quieter Pavement Research (QPR) study to investigate tire/pavement noise characteristics on concrete pavements. The On-board Sound Intensity (OBSI) method was used to measure tire/pavement noise.

In this third year of the study, a total of 83 pavement sections were tested at 35 different sites, which was reduced from the original 120 sections in the experiment for various reasons. Twenty-four of the 35 sites were divided into three test sections each, while the remaining eleven sites had one test section each that were used for analyses shown in this report. The third-year test sections were comprised of five texture types, with the following distribution of sections used in the analyses: 31 burlap drag, 23 diamond ground, 7 diamond grooved, 4 longitudinally broomed, and 18 longitudinally tined.

At this time no single concrete pavement texture type can be considered definitively quieter than the others. Each pavement type has a demonstrated range of noise levels that largely overlap. The difference between the lowest and highest OBSI levels for the same nominal texture type is up to 6 dBA, indicating a large variability within a given texture type when sampled over a wide range of ages. The contributions of joint width, faulting, and sealant overbanding to this variance have not been rigorously investigated, and the results to date include these effects, which are part of the total noise generated by concrete pavements in the state. Taking into account all sections, the OBSI level on existing concrete pavements in California varies from about 101.1 dBA to about 107.6 dBA. The ranking of texture types for the sections with *new* and *aged* textures evaluated in this research project from quietest to loudest is: longitudinally broomed, burlap drag, diamond ground, diamond grooved, and longitudinally tined, although the differences between the means of each of these textures is not statistically significant, except for the longitudinally broomed sections. The report includes results from the Mojave test sections on Kern 58 which were all constructed at the same time in 2003. Based on these observations and the conclusions to date, recommendations are made for the fourth and final year of large-scale data collection and analysis on concrete pavement noise to change the experiment to focus on the following textures: diamond ground, diamond grooved and longitudinally tined. Recommendations are also made to obtain more detailed data regarding texture characteristics, joint cross-sectional area, faulting, and sealant overbanding to try and better explain differences within each texture type.

Keywords: tire noise, OBSI, concrete pavements, texture types

Proposals for Implementation: No single texture type was found to be significantly quieter than the others across the set of sections for each type, which precludes the authors of this study from making a strong recommendation about their use for accomplishing noise reduction.

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)
- Ongel, A., E. Kohler, and J. Nelson. (2007) Acoustical Absorption of Open-Graded, Gap-Graded, and Dense-Graded Asphalt Pavements. (UCPRC-RR-2007-12)
- Ongel, A., J. T. Harvey, and E. Kohler. (2007) State of the Practice in 2006 for Open-Graded Asphalt Mix Design. (UCPRC-TM-2008-07)
- Ongel, A., N. Santero, and J. Harvey. (2005) Report of Field Site Visit District 3, Sacramento Interstate 5, PM 17.2-17.9 RAC-O Overlay. (UCPRC-TM-2005-07)
- Lu, Q., E. Kohler, J. T. Harvey, and A. Ongel. (2009) Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results. (UCPRC-RR-2009-01)
- Q. Lu, P. C. Fu, and J. T. Harvey. (2009) Laboratory Evaluation of the Noise and Durability Properties of Asphalt Surface Mixes. (UCPRC-RR-2009-07)
- Lu, Q., J.T. Harvey, and R. Wu. Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Four-Year Results. (2010) (UCPRC-RR-2010-05)
- 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)

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DISCLAIMER STATEMENT

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PROJECT OBJECTIVES

This project evaluated tire/pavement noise on rigid pavements for a third year on a set of concrete pavement field sections in California. The project has three objectives:

1. Identification of relationships between the design variables of concrete pavement surface textures used in California and tire/pavement noise characteristics,
2. Determination of trends in tire/pavement noise levels versus age for concrete pavements, and
3. Development of recommendations for surface textures that minimize tire/pavement noise.

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 Standards Team (PST) approved a research project to evaluate the tire/pavement noise characteristics and performance properties of existing flexible pavements, including current Caltrans open-graded mixes, dense- and gap-graded 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.

The quieter concrete pavement research study presented in this report was undertaken to determine the acoustic characteristics of the noise generated by tire/pavement interaction on concrete pavement surfaces, and to identify the types and properties of concrete surface textures that could effectively reduce tire/pavement noise. This study has three objectives:

1. Identify relationships between the design variables of concrete pavement surface textures and tire/pavement noise, covering the majority of surface textures used in California,
2. Determine trends in noise levels versus age for concrete pavements, and
3. Develop recommendations for concrete pavement surface textures that minimize tire/pavement noise.

This study involved the identification and monitoring of tire/pavement noise for three years of concrete pavement sections throughout the state. As the mechanisms of tire/pavement noise are affected by pavement surface texture, five different texture types were investigated in this project: burlap drag (BD), diamond ground (DG), diamond grooved (Gr), longitudinally broomed (LB), and longitudinally tined (LT). The pavement sections were assigned to surface texture–type categories based on visual observation and engineering judgment, not on the physical properties of the texture, which were not measured. After construction, surface textures change under the action of traffic, environmental influences, and the interaction of the two; this change is sometimes referred to as the *aging* of the textures. A consequence of this for this study was that in some cases, it became difficult to assign a texture type because of texture changes that had occurred within each texture type. For this reason, Caltrans construction data were searched for the year of construction or of the last retexturing for all test sections.

This project began in September 2008 with the identification of candidate pavement sections with a range of surface textures and surface ages representative of concrete pavements typically found on California highways. The final list of sections was selected from the candidates based on their texture type and age, and included a range of climate regions and traffic levels. Information about the concrete material in each section was unavailable. This is unfortunate since cement content, aggregate gradation, and other mix design variables affect the initial texturing and how it changes over time. As concrete surfaces are degraded by years of traffic and climate, the original texture is eventually worn away and the surface can no longer be considered representative of that texture. Based on recommendations from the Caltrans Quieter Pavement Research Task Group, sections included in this study were classified as having *new, aged,* or *worn out* textures, with these categories based on texture condition and not the age of the textures. The experiment was not designed as a well-balanced factorial experiment because it was intended as an initial study to assess existing pavements, and therefore it is not well balanced with respect to the age of the sections, traffic levels, or climate regions.

Chapter 2 of this report describes the data collection method, data reduction procedures, and the test section surface types, ages, and other details. Chapter 3 presents the various results relating the measured OBSI levels to each texture type and then to pavement surface age. Chapter 4 includes an analysis and discussion of the results. Chapter 5 presents conclusions.

Four appendices are included with this report. Appendix A presents bar charts with results of overall On-board Sound Intensity (OBSI) data obtained on all three testing years. Appendix B shows the calibration of the test tire used for data collection for this third year on PCC pavements, with the SRTT#1 tire used as a reference for all of the University of California Pavement Research Center (UCPRC) tire/pavement noise studies. Appendix C presents data and figures from OBSI measurements that have not been corrected for the tire and noise analyzer. Appendix D presents selected additional figures with more details regarding the data.

Tire/pavement noise was collected using the OBSI method as specified in AASHTO TP-76-09. Data was gathered on each section during three passes of five-second duration at 60 mph (96 km/hr), the typical OBSI procedure that was also followed in all other California Quieter Pavement Research studies. The data quality procedures incorporated into the AASHTO protocol were verified at the beginning and end of testing on each site rather than for every section since there were multiple back-to-back sections at most sites, a small deviation from the AASHTO procedure.

Besides the typical air density correction that takes into account the effect of air density on the speed of sound, two additional adjustments were considered necessary to normalize the results and to make them consistent with other OBSI databases. The results were converted to a particular test tire (the first Standard Reference Test Tire used by the UCPRC [SRTT#1]) and to a particular sound analyzer (the newer Harmonie four-channel analyzer). Appendix B presents the details of the tire and noise analyzer calibrations.

The details of all of the test sections, including classification into the five surface textures, last surface construction dates, and other information are presented in Chapter 2 of the report. The original set of test sections totaled 120 test sections at 47 sites, with 108 pavement sections at 36 sites (i.e., three sections per site), two sections at one site, and ten sites with one section each. Data collection spanned approximately three years: Year 1 between September 2008 and February 2009, Year 2 between September and December 2009, and Year 3 mostly between October 2010 and April 2011, with a few sections tested in August 2010 and June 2011. The extra time needed for testing in 2010/2011 was due to commitment of the test car to pavement condition survey quality assurance testing and weather delays.

A number of sections were dropped from the experiment over the three years due to construction or other issues that changed the sections. In the third year, the study included a total of 83 pavement sections at 35 different sites. Twenty-four of the 35 sites were divided into three test sections each, while the remaining eleven sites had one test section each that were used for analyses shown in this report. The third-year test sections were comprised of five texture types, with the following distribution of sections used in the analyses: 31 burlap drag, 23 diamond ground, 7 diamond grooved, 4 longitudinally broomed, and 18 longitudinally tined.

In Chapter 3, detailed results are shown for overall OBSI values as well as for frequency spectra content. The OBSI spectral contents are shown plotted to compare the OBSI results among the different texture types and texture conditions (*new, aged, worn out*). Results are also shown in Chapter 3 versus the time since construction of the surface texture.

The measured OBSI levels presented in this report include the effects of joint slap, faulting, and sealant, in addition to the effect of the pavement texture, each of which, 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 the joint below the surface acting as an amplifier for the sound of the tire passing over the joint. Faulting causes noise as the tire reacts to passing over the fault. Joint sealant that is present above the surface of the joint (referred to as *overbanded* sealant) creates positive texture which results in noise from tire vibration.

Faulting and overbanded sealant were not considered in the experiment used for this report and the previous two years of measurements because a method for measuring them using the high-speed profilometer had not been established, and photographs with sufficient detail to identify sealant overbanding were not available at the time the project scope was established. Additionally, measurement of joint opening cross-sectional area requires traffic closures, which were also not included in the project scope.

Chapter 4 includes a more detailed qualitative examination of each texture type, and also includes a comparison of the results from this study and those from several national studies of concrete tire/pavement noise.

Photographs in Chapter 4 show the surface textures on each of the Mojave sections (Kern 58), which are all of the same concrete mix and ages (with some textured in 2003 and others in 2006) and have been exposed to the same traffic and climate conditions. The quietest sections were those with a diamond-ground surface, and the loudest section had a longitudinally tined texture. The results from the Mojave sections were compared to the range of noise levels measured for each texture type on the other sections from across the state. That comparison showed that the burlap drag, diamond-ground, diamond-grooved, and longitudinally tined textures at Mojave were generally quieter than the same textures on the rest of the state highway network, while the longitudinally broomed texture at Mojave was noisier than the few longitudinally broomed sections measured on the rest of the network.

The conclusions and recommendations in the report address the primary purpose of this study, which was to evaluate the acoustic performance of concrete pavement surfaces in several experimental test sections and to quantify the impact of texture type and texture condition *(new, aged,* and *worn out)* on On-board Sound Intensity (OBSI) levels. To date this study has characterized the acoustic performance of concrete pavement surface texture types and quantified the impacts of texture type and condition on OBSI levels, with results obtained from OBSI measurements of tire/pavement interaction showing the following:

1. At this time no single concrete pavement texture type can be considered definitively quieter than the others. Each pavement type has a demonstrated range of noise levels that largely overlap.
2. The difference between the lowest and highest OBSI levels for the same nominal texture type is up to 6 dBA, indicating a large variability within a given texture type when sampled over a wide range of ages. The contributions of joint width, faulting, and sealant overbanding to this variance have not been rigorously investigated, and the results to date include these effects, which are part of the total noise generated by concrete pavements in the state.
3. Taking into account all sections, the OBSI level on existing concrete pavements in California varies from about 101.1 dBA to about 107.6 dBA.
4. If 105 dBA (based on the criterion separating the "Quality Zone" and the "Avoid Zone" from a 2006 National Concrete Pavement Technology Center [NCPTC] study) is selected as the upper threshold level that distinguishes between pavements with acceptable and unacceptable noise levels, about 52 percent of the burlap drag sections, 67 percent of the diamond-ground sections, 48 percent of the diamond-grooved sections, 100 percent of the longitudinally broomed sections, and 44 percent of the longitudinally tined sections tested for this study fall in the acceptable range.

5. The ranking of texture types for the sections with *new* and *aged* textures evaluated in this research project from quietest to loudest, is shown below.
   - Longitudinally broomed (n = 4, 102.5, *101.1 to 104.4)*
   - Burlap drag (n = 31, 104.3, *102.8 to 105.9)*
   - Diamond ground (n = 24, 104.4, *101.2 to 107.5)*
   - Diamond grooved (n = 7, 104.8, *102.1 to 107.6)*
   - Longitudinal tined (n = 18, 105.0, *102.7 to 106.8)*

   The first number following the texture type indicates the sample size, the second number indicates the average overall OBSI excluding the *worn out* texture condition averaged over three years of measurements, and the range of numbers in italic indicates the minimum and maximum values of overall OBSI excluding sections with *worn out* texture.
6. If a quieter pavement with an OBSI level less than 105 dBA (based on the NCPTC criterion) is needed, the data collected to date indicate that each of the textures evaluated can be used, however the characteristics of those textures that produce lower noise levels have not been clearly identified.
7. From these data, it is possible to identify a few sites that should be of interest for a more detailed investigation. These include the diamond-ground concrete pavement on US-50 (Yolo County), which is among the quietest pavements in this study and appears stable in terms of its acoustical durability, and the Mojave Desert sections, which have the same concrete mix design and experience the same traffic and environmental conditions.

In preparing for a fourth and final year of data collection and analysis on a large set of concrete pavement noise test sections, several observations are clear. First, the texture condition categorized by visual observation (*new, aged, worn out*) has not offered sufficient information to explain the reasons for variation in noise level within each texture type. It appears that a more in-depth characterization of the pavement textures—besides their nominal type and condition—is necessary to explain differences within texture type. Second, burlap drag does not appear to be a viable surface texture due to noise levels, although long-term data from the Mojave sections may later revive interest in this texture as well as in the longitudinally broomed texture. Third, the effects of joint width, faulting, and sealant overbanding on measured OBSI levels need to be considered.

Based on these observations and the conclusions to date, the following recommendations are made for the fourth and final year of large-scale data collection and analysis on concrete pavement noise:

1. Only include concrete pavements with diamond-grooving, diamond-grinding, and longitudinally tined surface textures, as well as the experimental New Generation Concrete Surface (NGCS) sections combining diamond-grinding and grooving, so that the factors that contribute to the wide range of OBSI values for these most promising texture types can be better understood.

2. Expand the experiment for these texture types to include more sites, and to be better balanced to create a factorial design with regard to age, traffic, and geographical location.
3. Consider faulting and sealant overbanding in the analysis of future data, and—using traffic closures—perform more detailed surface characterization on a subset of sections in the experiment; include measurement of joint widths and performance of texture scans in this characterization. These texture measurements can be used to see if characteristics of the joints and texture details help explain differences within each texture type for overall noise levels and frequency-by-frequency noise levels.
4. Test only one section at each site (the number of sections at each site is currently either one, two, or three) in order to simplify the field measurement, statistical analyses, and communication of the results. The reduction in the number of sections at each site will be offset by the increased number of sites which should produce a more widespread sample of each type of texture across the state. The data collected to date with multiple subsections has provided sufficient data needed to understand variability within sites.

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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 surfaces 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 flexible pavements, including current Caltrans open-graded mixes, dense- and gap-graded 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.

The quieter concrete pavement research study presented in this report was undertaken to determine the acoustic characteristics of the noise generated by tire/pavement interaction on concrete pavement surfaces, and to identify the types and properties of concrete surface textures that could effectively reduce tire/pavement noise. This study has three objectives:

1. Identify relationships between the design variables of concrete pavement surface textures and tire/pavement noise, covering the majority of surface textures used in California,
2. Determine trends in noise levels versus age for concrete pavements, and
3. Develop recommendations for concrete pavement surface textures that minimize tire/pavement noise.

This study involved the identification and monitoring for three years of 120 concrete pavement sections throughout the state. Field tests including tire/pavement noise measurements using the On-board Sound Intensity (OBSI) method were made at most of these sections once each year over a three-and-a-half-year period.

The mechanisms of tire/pavement noise are affected by pavement surface texture. Five different texture types were investigated in this project: burlap drag (BD), diamond ground (DG), diamond grooved (Gr), longitudinally broomed (LB), and longitudinally tined (LT).

The pavement sections were assigned to surface texture–type categories based on visual observation and engineering judgment, not on the physical properties of the texture, which were not measured. After construction, surface textures change under the action of traffic, environmental influences, and the interaction of the two; this change is sometimes referred to as the *aging* of the textures. A consequence of this for this study was that in some cases, it became difficult to assign a texture type because of texture changes that had occurred within each texture type. For this reason, Caltrans construction data were searched for the year of construction or of the last retexturing for all test sections.

This project began in September 2008 with the identification of candidate pavement sections with a range of surface textures and surface ages representative of concrete pavements typically found on California highways. The final list of sections was selected from the candidates based on their texture type and age, and included a range of climate regions and traffic levels. Information about the concrete material in each section was unavailable. This is unfortunate since cement content, aggregate gradation, and other mix design variables affect the initial texturing and how it changes over time. As concrete surfaces are degraded by years of traffic and climate, the original texture is eventually worn away and the surface can no longer be considered representative of that texture. Sections included in this study were classified as having *new, aged,* or *worn out* textures, with these categories based on texture condition and not the age of the textures. The experiment was not designed as a well-balanced factorial experiment because it was intended as an initial study to assess existing pavements, and therefore it is not well balanced with respect to the age of the sections, traffic levels, or climate regions.

As noted, the tire/pavement noise was measured on these sections using the OBSI method, the same method used for the flexible surface tire/pavement noise studies. The results were analyzed to determine overall OBSI levels and OBSI levels for different frequencies at one-third octave bands.

Chapter 2 of this report describes the data collection method, data reduction procedures, and the test section surface types, ages, and other details. Chapter 3 presents the various results relating the measured OBSI levels to each texture type and then to pavement surface age. Chapter 4 includes an analysis and discussion of the results. Chapter 5 presents conclusions.

Four appendices are included with this report. Appendix A presents bar charts with results of overall OBSI data obtained on all three testing years. Appendix B shows the calibration of the test tire used for data collection for this third year on PCC pavements, with the SRTT#1 tire used as a reference for all of the UCPRC tire/pavement noise studies. Appendix C presents data and figures from OBSI measurements that have not been corrected for the tire and analyzer. Appendix D presents selected additional figures with more details regarding the data.

2. DATA COLLECTION AND REDUCTION METHODS, AND TEST SECTION SELECTION

2.1 Data Collection

OBSI data was collected as specified in AASHTO TP-76-09 (*1*). Data was gathered on each section during three passes of five-second duration at 60 mph (96 km/hr), the typical OBSI procedure that was also followed in all other California Quieter Pavement Research studies. The data quality procedures incorporated into the AASHTO protocol were verified at the beginning and end of testing on each site rather than for every section since there were multiple back-to-back sections at most sites, a small deviation from the AASHTO procedure.

The sound analyzer for the OBSI measurements was programmed to collect three five-second periods of data in succession, creating three sections at each test site. In the first year of the three-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 non-homogeneity along each section (*2*). Some initial analysis was also performed regarding the effects of joint slap, as well as faulting and sealing of the joints on overall OBSI measurements, and that analysis of these joint effects on OBSI levels was summarized in the report on the first two years of this study (*2*). The field measurements under traffic closures necessary to isolate joint effects on OBSI will be part of the fourth year test plan for this study.

In addition to the use of the OBSI method to measure tire/pavement noise, an inertial profilometer was used to measure International Roughness Index (IRI) and Mean Profile Depth (MPD), and visual observations were made of the surface texture type and condition of each test section. The measured IRI values and texture observations were collected at the same fixed short intervals used for OBSI measurement. The instrumented vehicle used in this project is shown in Figure 2.1.

It should be noted that although IRI and macrotexture were collected as part of the first three years of this study, the lasers used on the profilometer are now generally considered to be inadequate for IRI and macrotexture measurement on directionally textured surfaces. Those lasers have very small contact areas which jump up and down on tined or grooved textures as the vehicle travels along the pavement, producing IRI values that are thought to be too high compared to the longitudinal profile elevation changes experienced by a tire much wider than the laser. Various organizations are investigating alternative lasers with wider footprints. There are other similar issues with MPD depending on the wander of the vehicle and on how straight the tines or grooves are in the longitudinal direction. For the reasons described above, the analysis in this report is constrained to the results of sound intensity measured by the OBSI method. A wider laser has been installed and calibrated for the planned fourth year of measurements on concrete pavement.

Figure 2.1: Instrumented vehicle with on-board sound intensity probes and an inertial profilometer.

2.2 Data Reduction

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 and for measurement inaccuracies due to 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 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.

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

Over the years that this technology has been used by University of California Pavement Research Center (UCPRC), there have been improvements to the process of OBSI data collection. For this research, OBSI data adjustments were 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 three years of data collection were Standard Reference Test Tires (SRTTs), an actual new SRTT was introduced in early November 2009 and was used for the 2010/2011 testing presented in this report to prevent 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 of the Year 1, Year 2, and Year 3 tires back to the first SRTT used by the UCPRC research team. The conversion made by the UCPRC adjusted the SRTT#2 (used in 2008), SRTT#3 (used in 2009), and SRTT#4 tires (used in 2010 and 2011) back to the SRTT#1 tire, the standard reference tire for all UCPRC noise studies. Use of a common reference tire (SRTT #1) will allow 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. In keeping with the practice of previous years, the tire correction equations used for the data in this report were developed using data from concrete pavements only, and are shown in Appendix B. For the next year's study and report, the tire calibration section data for that year's tire will be evaluated to determine whether a tire conversion equation using both the asphalt and concrete sections should be used for that year's data. That decision will be based on analysis of whether there is a significant effect of surface type.
b. Sound analyzer: A frequency-by-frequency correction was applied to account for the fact that a new sound analyzer was used for the second and third years of this study. Year 1 OBSI data were measured using two Larson Davis two-channel analyzers, while a Sinus Harmonie four-channel analyzer was used in Year 2 and Year 3 using data from both asphalt and concrete sections because there was no interaction of surface type and the two analyzers. Linear transformation equations were determined using results from field sections tested with both analyzers, and the results that had previously been measured with the Larson Davis analyzers were converted to equivalent Sinus Harmonie analyzer results. The analyzer correction equations were developed using data from both asphalt and concrete pavements. 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 possibly introduce 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 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 (*3*) presented a paper at the Transportation Research Board conference based on measurements performed as part of NCHRP Project 1-41(1) (*4*) 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. Based on Donavan and Lodico's proposed guidelines, the UCPRC decision to change the tire between the two testing periods of the study (2009 and 2010/2011), and each year subsequently, was justified.

The paper by Donavan and Lodico also recommends that data relating the properties of different SRTT tires, such as age, miles travelled, hardness and tread depths, should be collected in order to better understand how they affect OBSI measurements. The annual calibration of the new UCPRC tire to previously used tires and the current UCPRC practices of measuring hardness and tread depth, tracking accumulated miles, and developing frequency-by-frequency as well as overall OBSI statistical correlations between tires will provide data for such a database. This database will be important 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.

To help understand the effects of changing the tire between the two years of data collection, the uncorrected data and the corrected data are both included in the same table in Appendix C, along with plots of selected figures from the main body of the report that have been replotted with uncorrected data. All results in the main body of the report are with corrected OBSI values.

It should be noted that no temperature correction has been applied to the data in this report. UCPRC has previously developed corrections for air temperature based on UCPRC testing at two sites (5), but has not included them in reports.

2.3 Description of the Test Sections

The details of all of the test sections, including classification into the five surface textures, last surface construction dates, and other information are presented in Table 2.1. Section selection was based on the process explained in Chapter 1. The original set of test sections totaled 120 test sections at 47 sites, with 108 pavement sections at 36 sites (i.e., three sections per site), two sections at one site, and ten sites with one section each. Data collection spanned approximately three years: Year 1 between September 2008 and February 2009, Year 2 between September and December 2009, and Year 3 mostly between October 2010 and April 2011, with a few sections tested in August 2010 and June 2011. The extra time needed for testing in 2010/2011 was due to commitment of the test car to pavement condition survey quality assurance testing and weather delays.

A number of sections were dropped from the experiment over the three years due to construction or other issues that changed the sections. In the third year, the study included a total of 83 pavement sections at 35 different sites. Twenty-four of the 35 sites were divided into three test sections each, while the remaining eleven sites had one test section each that were used for the analyses shown in this report. The third-year test sections were comprised of five texture types, with the following distribution of sections used in the analyses: 31 burlap drag, 23 diamond ground, 7 diamond grooved, 4 longitudinally broomed, and 18 longitudinally tined.

Figure 2.2 shows the counties in which the original 120 sections were located (shaded orange). The complete list of test sections sorted by section number is presented in Table 2.1.

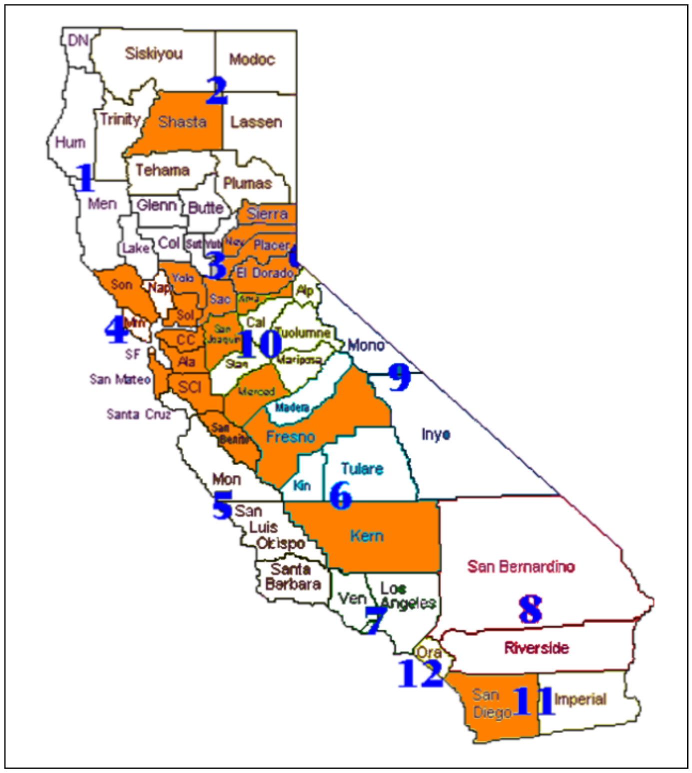


Figure 2.2: Map showing counties in which the original study sections were located.

Table 2.1: List of Locations, Texture Types and Conditions, and Construction and Resurfacing Years of Field Evaluation Sections

Section ID	Location: Dist-Cnty-Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Cond.[3]	Date/Time of Collection in Year 1	Date/Time of Collection in Year 2	Date/Time of Collection in Year 3	OBSI Level Year 1	OBSI Level Year 2	OBSI Level Year 3
QP-100.1	03Yol113N3.0	2 of 2	LT	1976	7/1/1976	Aged	9/3/2008	9/4/2009	10/5/2010	103.1	105.3	105.3
QP-100.2	03Yol113N3.1	2 of 2	LT	1976	7/1/1976	Aged	9/3/2008	9/4/2009	10/5/2010	104.7	106.8	106.8
QP-100.3	03Yol113N3.2	2 of 2	LT	1976	7/1/1976	Aged	9/3/2008	9/4/2009	10/5/2010	103.7	105.6	105.6
QP-101.1	03Yol113N6.0	2 of 2	LT	1990	7/1/1990	Aged	9/23/2008	9/4/2009	10/5/2010	105.2	106.7	106.7
QP-101.2	03Yol113N6.1	2 of 2	LT	1990	7/1/1990	Aged	9/23/2008	9/4/2009	10/5/2010	105.5	106.7	106.7
QP-101.3	03Yol113N6.2	2 of 2	LT	1990	7/1/1990	Aged	9/23/2008	9/4/2009	10/5/2010	105.2	106.8	106.8
QP-102.1	03Yol113S5.5	2 of 2	BD	1976	7/1/1976	Worn out	9/23/2008	9/4/2009	10/5/2010	101.1	103.3	103.3
QP-102.2	03Yol113S5.4	2 of 2	BD	1976	7/1/1976	Worn out	9/23/2008	9/4/2009	10/5/2010	100.7	103	103
QP-102.3	03Yol113S5.3	2 of 2	BD	1976	7/1/1976	Worn out	9/23/2008	9/4/2009	10/5/2010	100.8	103	103
QP-103.1	03Yol50E0.2	1 of 4	DG	1969	7/1/2005	Aged	10/2/2008	Not tested	4/22/2011	99.8		
QP-103.2	03Yol50E0.3	1 of 4	DG	1969	7/1/2005	Aged	10/2/2008	Not tested	4/22/2011	99.6		
QP-103.3	03Yol50E0.4	1 of 4	DG	1969	7/1/2005	Aged	10/2/2008	Not tested	4/22/2011	99.4		
QP-104.1	03Sac50E3.2	1 of 5	BD	1971	7/1/1971	Worn out	10/3/2008	9/11/2009	1/10/2011	103.5	105	105
QP-104.2	03Sac50E3.2	1 of 5	BD	1971	7/1/1971	Worn out	10/3/2008	9/11/2009	1/10/2011	104.1	105.4	105.4
QP-104.3	03Sac50E3.2	1 of 5	BD	1971	7/1/1971	Worn out	10/3/2008	9/11/2009	1/10/2011	104.7	105.5	105.5
QP-105.1	03Sac50E4.0	1 of 4	BD	1971	7/1/1971	Worn out	10/3/2008	9/11/2009	1/10/2011	102.9	104.8	104.8
QP-105.2	03Sac50E4.1	1 of 4	BD	1971	7/1/1971	Worn out	10/3/2008	9/11/2009	1/10/2011	103.6	104.8	104.8
QP-105.3	03Sac50E4.2	1 of 4	BD	1971	7/1/1971	Worn out	10/3/2008	9/11/2009	1/10/2011	103	104.7	104.7
QP-106.1	03Sac50E10.5	1 of 5	BD	1973	7/1/1973	Worn out	10/13/2008	9/11/2009	8/12/2010	101.9	103.6	103.6
QP-106.2	03Sac50E10.6	1 of 5	BD	1973	7/1/1973	Worn out	10/13/2008	9/11/2009	8/12/2010	102.4	104.1	104.1
QP-106.3	03Sac50E10.7	1 of 5	BD	1973	7/1/1973	Worn out	10/13/2008	9/11/2009	8/12/2010	102.6	103.8	103.8
QP-107.1	03Sac80E13.6	5 of 5	BD	1973	7/1/1973	Worn out	10/16/2008	9/9/2009	2/11/2011	103.2	104.9	104.9
QP-107.2	03Sac80E13.7	5 of 5	BD	1973	7/1/1973	Worn out	10/16/2008	9/9/2009	2/11/2011	102.6	104.2	104.2
QP-107.3	03Sac80E13.8	5 of 5	BD	1973	7/1/1973	Worn out	10/16/2008	9/9/2009	2/11/2011	101.7	103.7	103.7
QP-108.1	03Pla80E45.0	1 of 2	LT	1961	7/1/2004	Worn out	10/21/2008	9/16/2009	6/20/2011	104.5	105.8	105.8
QP-108.2	03Pla80E45.1	1 of 2	LT	1961	7/1/2004	Worn out	10/21/2008	9/16/2009	6/20/2011	104.7	105.7	105.7

Section ID	Location: Dist-Cnty-Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Cond.[3]	Date/Time of Collection in Year 1	Date/Time of Collection in Year 2	Date/Time of Collection in Year 3	OBSI Level Year 1	OBSI Level Year 2	OBSI Level Year 3
QP-108.3	03Pla80E45.2	1 of 2	LT	1961	7/1/2004	Worn out	10/21/2008	9/16/2009	6/20/2011	103.9	105.5	105.5
QP-109.1	03Nev80E22.6	1 of 2	LB	1989	7/1/1989	Worn out	10/21/2008	Not tested	Not tested	102.2		
QP-109.2	03Nev80E22.6	1 of 2	LB	1989	7/1/1989	Worn out	10/21/2008	Not tested	Not tested	102.7		
QP-109.3	03Nev80E22.6	1 of 2	LB	1989	7/1/1989	Worn out	10/21/2008	Not tested	Not tested	101.9		
QP-110.1	03Nev80E24.0	1 of 3	Gr	1989	7/1/1996	Aged	10/21/2008	Not tested	Not tested	102		
QP-110.2	03Nev80E24.1	1 of 3	Gr	1989	7/1/1996	Aged	10/21/2008	Not tested	Not tested	102		
QP-110.3	03Nev80E24.2	1 of 3	Gr	1989	7/1/1996	Aged	10/21/2008	Not tested	Not tested	101.9		
QP-111.1	03Nev80W24.2	1 of 2	Gr	1989	7/1/1996	Aged	10/21/2008	Not tested	Not tested	103.2		
QP-111.2	03Nev80W24.1	1 of 2	Gr	1989	7/1/1996	Aged	10/21/2008	Not tested	Not tested	103.1		
QP-111.3	03Nev80W24.0	1 of 2	Gr	1989	7/1/1996	Aged	10/21/2008	Not tested	Not tested	102.7		
QP-112.1	03Nev80W23.0	1 of 2	LB	1989	7/1/1989	Worn out	10/21/2008	Not tested	Not tested	102.1		
QP-112.2	03Nev80W22.9	1 of 2	LB	1989	7/1/1989	Worn out	10/21/2008	Not tested	Not tested	102.7		
QP-112.3	03Nev80W22.8	1 of 2	LB	1989	7/1/1989	Worn out	10/21/2008	Not tested	Not tested	104.1		
QP-113.1	03Yol80W22.9	1 of 3	BD	1965	7/1/1965	Worn out	10/23/2008	Not tested	Not tested	103.9		
QP-113.2	03Yol80W22.8	1 of 3	BD	1965	7/1/1965	Worn out	10/23/2008	Not tested	Not tested	104.4		
QP-113.3	03Yol80W22.7	1 of 3	BD	1965	7/1/1965	Worn out	10/23/2008	Not tested	Not tested	103.6		
QP-114.1	04Sol80W18.7	2 of 4	DG	1949	7/1/1999	Aged	10/23/2008	Not tested	Not tested	102.3		
QP-114.2	04Sol80W18.6	2 of 4	DG	1949	7/1/1999	Aged	10/23/2008	Not tested	Not tested	102		
QP-114.3	04Sol80W18.5	2 of 4	DG	1949	7/1/1999	Aged	10/23/2008	Not tested	Not tested	102.6		
QP-115.2	03Yol505S13.0	2 of 2	BD	1977	7/1/1977	Aged	10/27/2008	9/8/2009	10/8/2010	103.3	105	105
QP-115.3	03Yol505S12.9	2 of 2	BD	1977	7/1/1977	Aged	10/27/2008	9/8/2009	10/8/2010	103.3	105	105
QP-116.1	04Sol80E32.0	1 of 3	BD	1946	7/1/1946	Worn out	10/28/2008	9/10/2009	2/11/2011	106.5	107.8	107.8
QP-116.2	04Sol80E32.1	1 of 3	BD	1946	7/1/1946	Worn out	10/28/2008	9/10/2009	2/11/2011	106.3	107.3	107.3
QP-116.3	04Sol80E32.2	1 of 3	BD	1946	7/1/1946	Worn out	10/28/2008	9/10/2009	2/11/2011	105.7	107	107
QP-117.1	04CC80W10.3	4 of 4	LT	2007	7/1/2007	New	10/28/2008	10/29/2009	2/9/2011	103.1	106.3	106.3
QP-117.2	04CC80W10.2	4 of 4	LT	2007	7/1/2007	New	10/28/2008	10/29/2009	2/9/2011	102.7	106.3	106.3
QP-117.3	04CC80W10.1	4 of 4	LT	2007	7/1/2007	New	10/28/2008	10/29/2009	2/9/2011	102.9	106.4	106.4

Section ID	Location: Dist-Cnty-Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Cond.[3]	Date/Time of Collection in Year 1	Date/Time of Collection in Year 2	Date/Time of Collection in Year 3	OBSI Level Year 1	OBSI Level Year 2	OBSI Level Year 3
QP-123.1	04ALA580E37.1	4 of 4	BD	1965	7/1/1965	Aged	11/5/2008	11/12/2009	2/8/2011	104.2	105.5	105.5
QP-123.2	04ALA580E37.2	4 of 4	BD	1965	7/1/1965	Aged	11/5/2008	11/12/2009	2/8/2011	104	104.6	104.6
QP-123.3	04ALA580E37.3	4 of 4	BD	1965	7/1/1965	Aged	11/5/2008	11/12/2009	2/8/2011	103.9	105.1	105.1
QP-126.1	04SCL85S21.5L3	3 of 3	BD	1965	7/1/1965	Worn out	11/7/2008	11/18/2009	4/20/2011	107	107.4	107.4
QP-126.2	04SCL85S21.4L3	3 of 3	BD	1965	7/1/1965	Worn out	11/7/2008	11/18/2009	4/20/2011	105.8	106.7	106.7
QP-126.3	04SCL85S21.3L3	3 of 3	BD	1965	7/1/1965	Worn out	11/7/2008	11/18/2009	4/20/2011	106.9	107.4	107.4
QP-127.1	04SCL85S21.5L1	1 of 3	LT	1965	7/1/1965	Aged	11/7/2008	11/18/2009	4/20/2011	103.2	104.6	104.6
QP-127.2	04SCL85S21.4L1	1 of 3	LT	1965	7/1/1965	Aged	11/7/2008	11/18/2009	4/20/2011	103.7	105.1	105.1
QP-127.3	04SCL85S21.3L1	1 of 3	LT	1965	7/1/1965	Aged	11/7/2008	11/18/2009	4/20/2011	103.1	104.5	104.5
QP-128.1	04SCL85N14.8	3 of 3	DG	1993	7/1/2006	Aged	11/7/2008	11/18/2009	4/20/2011	103	104.2	104.2
QP-128.2	04SCL85N14.9	3 of 3	DG	1993	7/1/2006	Aged	11/7/2008	11/18/2009	4/20/2011	102.9	104.1	104.1
QP-128.3	04SCL85N14.10	3 of 3	DG	1993	7/1/2006	Aged	11/7/2008	11/18/2009	4/20/2011	101.6	103.1	103.1
QP-129.1	06FRE180W55.7	3 of 3	LT	2008	7/1/2008	Aged	11/10/2008	11/13/2009	2/24/2011	103.6	105	105
QP-129.2	06FRE180W55.6	3 of 3	LT	2008	7/1/2008	Aged	11/10/2008	11/13/2009	2/24/2011	103.7	104.8	104.8
QP-129.3	06FRE180W55.5	3 of 3	DG	2008	7/1/2008	New	11/10/2008	11/13/2009	2/24/2011	103.3	104.6	104.6
QP-130.1	11SD5S39.7	4 of 4	BD	1964	7/1/1964	Worn out	11/11/2008	11/22/2009	12/15/2010	106.9	107.3	107.3
QP-130.2	11SD5S39.6	4 of 4	BD	1964	7/1/1964	Worn out	11/11/2008	11/22/2009	12/15/2010	106.6	107.1	107.1
QP-130.3	11SD5S39.5	4 of 4	BD	1964	7/1/1964	Worn out	11/11/2008	11/22/2009	12/15/2010	106.8	107.1	107.1
QP-131.1	11SD8W15.5	1 of 3	DG	1985	7/1/1997	Aged	11/11/2008	11/23/2009	12/15/2010	105.3	103.7	103.7
QP-131.2	11SD8W15.6	1 of 3	DG	1985	7/1/1997	Aged	11/11/2008	11/23/2009	12/15/2010	105.1	103.6	103.6
QP-131.3	11SD8W15.7	1 of 3	DG	1985	7/1/1997	Aged	11/11/2008	11/23/2009	12/15/2010	105.2	103.6	103.6
QP-132.1	11SD805N2.1	5 of 5	DG	1975	7/1/1998	Aged	11/12/2008	11/24/2009	12/16/2010	105.4	106.3	106.3
QP-132.2	11SD805N2.2	5 of 5	DG	1975	7/1/1998	Aged	11/12/2008	11/24/2009	12/16/2010	106.6	107.2	107.2
QP-132.3	11SD805N2.3	5 of 5	DG	1975	7/1/1998	Aged	11/12/2008	11/24/2009	12/16/2010	106	107.3	107.3
QP-133.1	11SD805N2.3	4 of 4	DG	1975	7/1/1998	Aged	11/12/2008	11/24/2009	12/16/2010	106.5	106.4	106.4
QP-133.2	11SD805N2.4	4 of 4	DG	1975	7/1/1998	Aged	11/12/2008	11/24/2009	12/16/2010		107.3	107.3[4]
QP-134.1	11SD905W5.2	2 of 2	DG	1975	7/1/2000	Aged	11/12/2008	11/24/2009	12/16/2010	105	106.4	106.4

Section ID	Location: Dist-Cnty-Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Cond.[3]	Date/Time of Collection in Year 1	Date/Time of Collection in Year 2	Date/Time of Collection in Year 3	OBSI Level Year 1	OBSI Level Year 2	OBSI Level Year 3
QP-134.2	11SD905W5.1	2 of 2	DG	1975	7/1/2000	Aged	11/12/2008	11/24/2009	12/16/2010	104.9	104.9	104.9
QP-134.3	11SD905W5.0	2 of 2	DG	1975	7/1/2000	Aged	11/12/2008	11/24/2009	12/16/2010	106.2	106.4	106.4
QP-135.1	04SON101N25.4L2	2 of 2	DG	1962	7/1/2006	Aged	11/17/2008	Not tested		103.4		
QP-135.2	04SON101N25.5L2	2 of 2	DG	1962	7/1/2006	Aged	11/17/2008	Not tested		103.5		
QP-135.3	04SON101N25.6L2	2 of 2	DG	1962	7/1/2006	Aged	11/17/2008	Not tested		103.7		
QP-136.1	04SON101S27.3L2	2 of 2	Gr	1962	7/1/2006	Aged	11/17/2008	Not tested		103.8		
QP-136.2	04SON101S27.2L2	2 of 2	Gr	1962	7/1/2006	Aged	11/17/2008	Not tested		103.6		
QP-136.3	04SON101S27.1L2	2 of 2	Gr	1962	7/1/2006	Aged	11/17/2008	Not tested		103.8		
QP-137.1	04SON101N25.4L1	1 of 2	BD	1962	7/1/1962	Aged	11/17/2008	Not tested		102.2		
QP-137.2	04SON101N25.5L1	1 of 2	BD	1962	7/1/1962	Aged	11/17/2008	Not tested		103.1		
QP-137.3	04SON101N25.6L1	1 of 2	BD	1962	7/1/1962	Aged	11/17/2008	Not tested		102.8		
QP-138.1	04SON101S27.3L1	1 of 2	Gr	1962	7/1/2006	Aged	11/17/2008	Not tested		103.1		
QP-138.2	04SON101S27.2L1	1 of 2	Gr	1962	7/1/2006	Aged	11/17/2008	Not tested		103		
QP-138.3	04SON101S27.1L1	1 of 2	Gr	1962	7/1/2006	Aged	11/17/2008	Not tested		101.7		
QP-142.1	03NEV80W1.0	2 of 2	LT	2008	7/1/2008	New	11/24/2008	9/17/2009	6/21/2011	104.9	111.4	111.4[5]
QP-142.2	03NEV80W0.9	2 of 2	LT	2008	7/1/2008	New	11/24/2008	9/17/2009	6/21/2011	104.5	111.2	111.2[5]
QP-142.3	03NEV80W0.8	2 of 2	LT	2008	7/1/2008	New	11/24/2008	9/17/2009	6/21/2011	103.9	112.6	112.6[5]
QP-146.1	04SM280N10.6	1 of 4	LB	1974	7/1/1974	Aged	12/2/2008	11/16/2009	3/1/2011	101.4	102.7	102.7
QP-146.2	04SM280N10.7	1 of 4	LB	1974	7/1/1974	Aged	12/2/2008	11/16/2009	3/1/2011	101.2	102.2	102.2
QP-146.3	04SM280N10.8	1 of 4	LB	1974	7/1/1974	Aged	12/2/2008	11/16/2009	3/1/2011	101.1	102.1	102.1
QP-147.1	04SM280N11.6	1 of 3	DG	1973	7/1/2007	New	12/2/2008	11/16/2009	3/1/2011	102.5	102.9	102.9
QP-147.2	04SM280N11.7	1 of 3	DG	1973	7/1/2007	New	12/2/2008	11/16/2009	3/1/2011	102.8	103	103
QP-147.3	04SM280N11.8	1 of 3	DG	1973	7/1/2007	New	12/2/2008	11/16/2009	3/1/2011	102.7	103.4	103.4
QP-148.1	04SM280N1.6	1 of 4	DG	1969	7/1/2001	Aged	12/3/2008	11/16/2009	4/19/2011	102.9	103.4	103.4
QP-148.2	04SM280N1.7	1 of 4	DG	1969	7/1/2001	Aged	12/3/2008	11/16/2009	4/19/2011	103	103.6	103.6
QP-148.3	04SM280N1.8	1 of 4	DG	1969	7/1/2001	Aged	12/3/2008	11/16/2009	4/19/2011	103.2	103.7	103.7
QP-153.1	10Mer99S17.5	1 of 2	Gr	1962	7/1/2006	Aged	12/17/2008	11/13/2009	2/24/2011	105.1	106.1	106.1

Section ID	Location: Dist-Cnty-Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Cond.[3]	Date/Time of Collection in Year 1	Date/Time of Collection in Year 2	Date/Time of Collection in Year 3	OBSI Level Year 1	OBSI Level Year 2	OBSI Level Year 3
QP-153.2	10Mer99S17.4	1 of 2	Gr	1962	7/1/2006	Aged	12/17/2008	11/13/2009	2/24/2011	105.6	106.3	106.3
QP-153.3	10Mer99S17.3	1 of 2	Gr	1962	7/1/2006	Aged	12/17/2008	11/13/2009	2/24/2011	105.1	105.9	105.9
QP-154.1	06Ker58E110.2	2 of 2	Gr	2003	7/1/2006	Aged	1/8/2009	12/2/2009	3/22/2011	102.1	103.7	103.7
QP-155.1	06Ker58E110.6	2 of 2	DG	2003	7/1/2006	Aged	1/8/2009	12/2/2009	3/23/2011	101.2	101.7	101.7
QP-156.1	06Ker58E111.2	2 of 2	Gr	2003	7/1/2006	Aged	1/9/2009	12/2/2009	3/22/2011	103.7	104.7	104.7
QP-157.1	06Ker58E111.4	2 of 2	Gr	2003	7/1/2006	Aged	1/9/2009	12/2/2009	3/23/2011	102.1	103.2	103.2
QP-158.1	06Ker58E109.5	2 of 2	LT	2003	7/1/2003	Aged	1/9/2009	12/2/2009	3/22/2011	103.6	104.4	104.4
QP-159.1	06Ker58E110.3	2 of 2	BD	2003	7/1/2003	Aged	1/9/2009	12/3/2009	3/23/2011	101.9	102.2	102.2
QP-160.1	06Ker58E110.0	2 of 2	DG	2003	7/1/2006	Aged	2/23/2009	12/2/2009	3/23/2011	102.7	102.9	102.9
QP-161.1	06Ker58E110.4	2 of 2	Gr	2003	7/1/2006	Aged	2/23/2009	12/3/2009	3/23/2011	103.2	103.2	103.2
QP-162.1	06Ker58E111.5	2 of 2	LB	2003	7/1/2003	Aged	2/24/2009	12/3/2009	3/23/2011	102.5	103	103
QP-166.1	06Ker58E111.7	2 of 2	DG	2003	7/1/2006	Aged	2/26/2009	12/2/2009	3/22/2011	101.7	103	103

Notes:

1. Lane # of total lanes (Lane #1 is next to the median.)

2. Texture Type:

BD = burlap drag

DG = diamond ground

Gr = diamond grooved

LB = longitudinally broomed

LT = longitudinally tined

3. Texture Condition:

New = Sections that had been open to traffic for less than a year at the time of the first measurements

Aged = Sections where the texture could be observed in the wheelpaths

Worn out = Sections where the texture had been worn out in the wheelpaths by traffic

4. Data not used in statistical analyses because of uncertainty about exact location in first year of measurement.

5. Data not used because of high chain wear.

2.4 Description of Texture Types and Texture Condition Categories

Five pavement surface texture types were identified for this study. Table 2.2 lists the surface texture types, the number of sections evaluated in each year of the study for each texture type, and the pavement sites in which the sections were located.

Table 2.2: Texture Types and Sections

Texture Type	Number of Sections Used in Analyses	Sites
Burlap drag (BD)	Year 1: 37 Year 2: 31 Year 3: 31	QP-102, QP-104, QP-105, QP-106, QP-107, QP-113, QP-115, QP-116, QP-123, QP-126, QP-130, QP-137, and QP-159. By Years 2 and 3, the six sections at Sites QP-113 and QP-137 had been overlaid.
Diamond ground (DG)	Year 1: 32 Year 2: 24 Year 3: 23	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. The nine sections at Sites QP-103, QP-114, and QP-135 were overlaid or had lane shift by Year 2. Section QP-132.2 was not tested in Year 1 due to operator error, but it was tested in Years 2 and 3; data was not used in statistical analyses.
Diamond grooved (Gr)	Year 1: 19 Year 2: 7 Year 3: 7	QP-110, QP-111, QP-136, QP-138, QP-153, QP-154, QP-156, QP-157, and QP-161. The first four of these sites (with a total of 12 sections) were overlaid by Year 2, therefore they are not included in Years 2 and 3.
Longitudinally broomed (LB)	Year 1: 10 Year 2: 4 Year 3: 4	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.
Longitudinally tined (LT)	Year 1: 21 Year 2: 21 Year 3: 18	QP-100, QP-101, QP-108, QP-117, QP-127, QP-129.1 and QP-129.2, QP-142, and QP-158. QP-142 was not used in analyses due to high chain wear.

In most cases the assessment of surface type was initially done in the field by windshield survey at highway speed and then confirmed by observation from the shoulder. The texture type assignment made in the first year of the study was checked at the beginning of the third year of measurements using photographs taken from the shoulder in the first two years. It was not possible to obtain information on the mixes, such as aggregate gradation. It should be noted that all but one of the sections classified as burlap drag (BD) were originally constructed before 1977. It is possible that the BD sections previously had another type of texture that was completely worn off, leaving no evidence that it existed anywhere on the slabs. Diamond grinding is a technique commonly used in California to correct texture and profile. Older diamond-ground sections included in this study were about 13 years old. The longitudinally broomed pavement surface texture is not commonly found on California highways. Longitudinal tining is the texture type most commonly used on California highways.

Based upon the recommendations of the Quieter Pavement Research Task Group, pavements were divided into three texture condition categories based on visual observation of the surface texture conditions:

- *New,* defined as a surface that had been open to traffic for less than a year at the time of the first measurements in September 2008, or the surface was determined to have maintained its texture in a condition like new.
- *Aged,* defined as a surface where the wheelpaths showed signs of texture abrasion but the texture could still be observed.
- *Worn out,* defined as a surface where traffic had completely worn off the texture from the wheelpaths.

The number of sections in each texture type and condition category is shown in Table 2.3, summarized from the section-by-section information in Table 2.1. It can be seen in Table 2.3 that for some texture types there is no data for one or two of the three categories. These include longitudinally broomed in the *new* condition, burlap drag in the *new* condition, diamond ground in the *worn out* condition, and diamond grooved in the *new* and *worn out* conditions.

Table 2.3: Texture Types and Conditions

Texture Type	Texture Condition	Year 1		Year 2		Year 3	
		Number of Sites	Number of Sections	Number of Sites	Number of Sections	Number of Sites	Number of Sections
LT	New	2	6	2	6	2	6
	Aged	5	12	5	12	5	12
	Worn out	1	3	1	3	1	3
LB	New	0	0	0	0	0	0
	Aged	2	4	2	4	2	4
	Worn out	2	6	0	0	0	0
BD	New	0	0	0	0	0	0
	Aged	4	10	3	7	3	7
	Worn out	9	27	8	24	8	24
DG	New	3	6	3	6	3	6
	Aged	10	26	7	18	8	21
	Worn out	0	0	0	0	0	0
Gr	New	0	0	0	0	0	0
	Aged	6	19	2	7	2	7
	Worn out	0	0	0	0	0	0

2.5 Lane Locations of Sections

Table 2.4 lists the locations of the test sections for this third year of measurements. All test sections at a site were in the same lane, however the test lanes at the sites varied as follows: 60 of the 120 sections were on the outside lane, 57 were on the inside lane, and 3 were on the middle lane.

Table 2.4: Lane Locations of Sections Used in Year 3 Measurements

Test Lane and Total Number of Lanes		Number of Sections	
Outside	2 of 2	34	60
	3 of 3	9	
	4 of 4	11	
	5 of 5	6	
Inside	1 of 2	21	57
	1 of 3	18	
	1 of 4	12	
	1 of 5	6	
Middle	2 of 4	3	3

3. RESULTS

3.1 Results by Texture Type and Texture Condition

The OBSI spectral contents were plotted to compare the OBSI results among the different texture types. However, after examination of the changes of the spectra from Year 1 to Year 2 and Year 2 to Year 3, a decision was made to use each section's three-year average spectra and only include those sections where three years of measurements were available. This approach was deemed a better one than trying to track the year-to-year changes over the three years because the changes were very small relative to the variability of the results. To simplify the comparison even further, the spectra of three subsections from a given site were also averaged and depicted in graphs as one rather than as three sections. The legend in each graph shows whether a single line represents only one section or if the result comes from a site with three sections. The construction year for each surface is also included in the legend.

As mentioned in Section 2.4, an attempt was made to categorize the texture on each section into one of three texture condition categories*: new, aged,* or *worn out.*

3.1.1 Burlap Drag Sections

There were no sections with burlap drag texture in the *new* texture category. The texture *aged* and texture *worn out* sections are shown in Figure 3.1 and Figure 3.2 respectively. A comparison of the average spectral content for the two conditions is shown in Figure 3.3. These figures show that the burlap drag texture exhibits a high noise level at low frequencies around 800 Hz. For one-third octave band frequencies below 1,000 Hz, the spectra for the sections with the *worn out* texture have sound intensity levels about 1 to 2 dB greater than for *aged* texture sections.

3.1.2 Diamond-Ground Sections

There were no diamond-ground sections in the *worn out* texture category. The *new* texture and *aged* texture sections are shown in Figure 3.4 and Figure 3.5 respectively. A comparison of the average spectral content for the two texture conditions is shown in Figure 3.6. The comparison indicates that the wearing out of the texture increases the high frequency noise content.

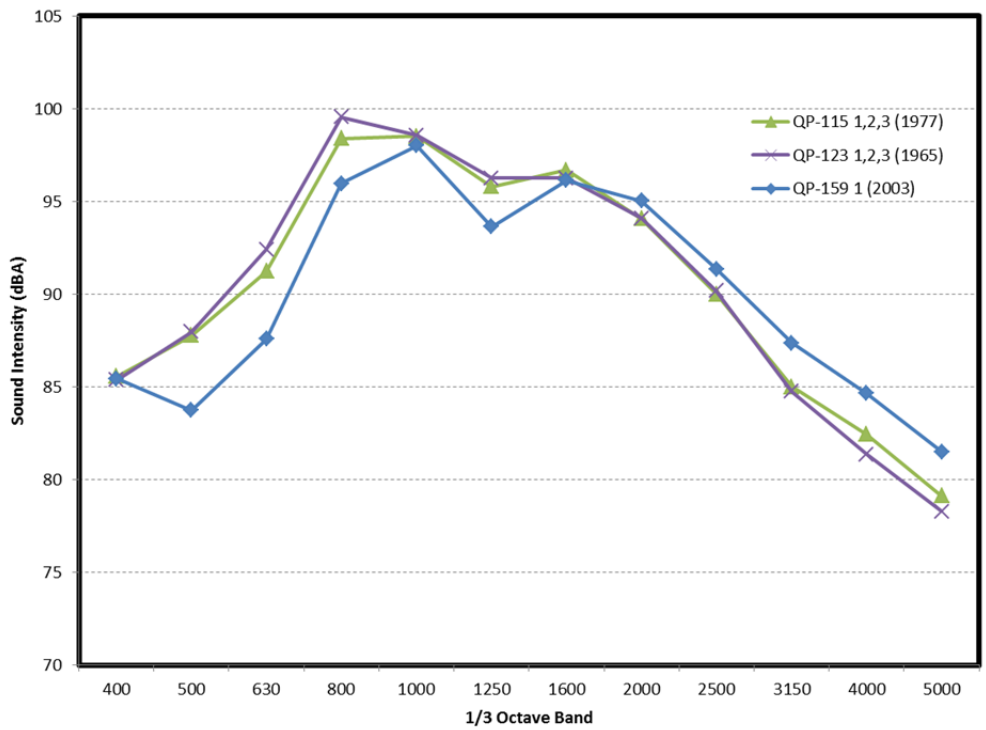


Figure 3.1: OBSI spectral content for burlap drag sections, texture *aged.*

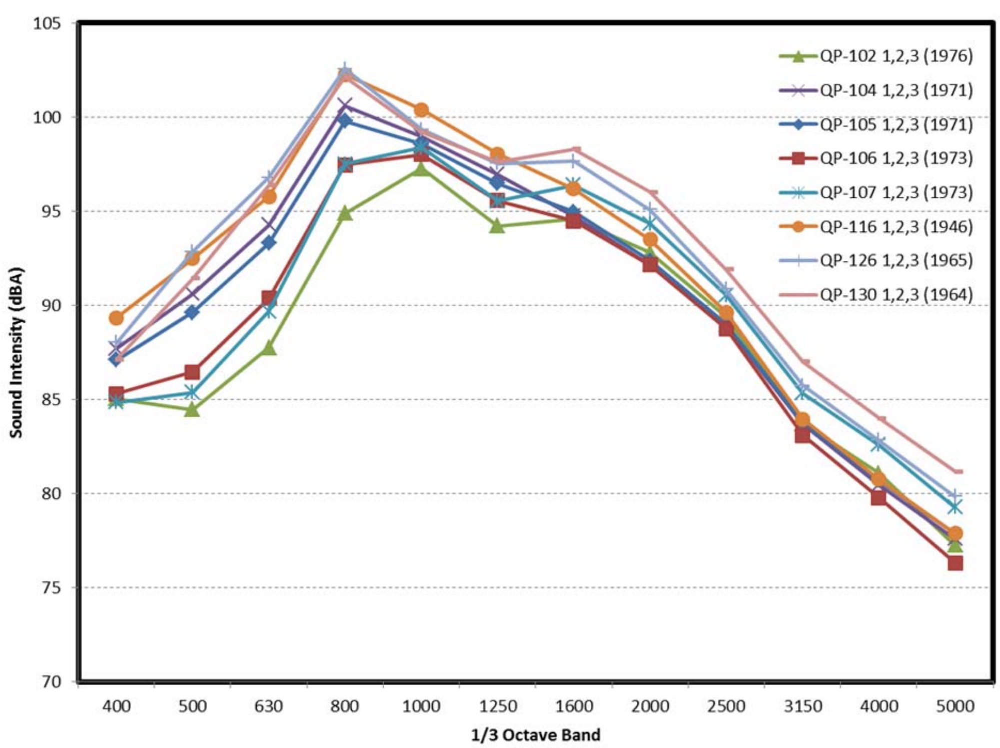


Figure 3.2: OBSI spectral content for burlap drag sections, texture *worn out.*

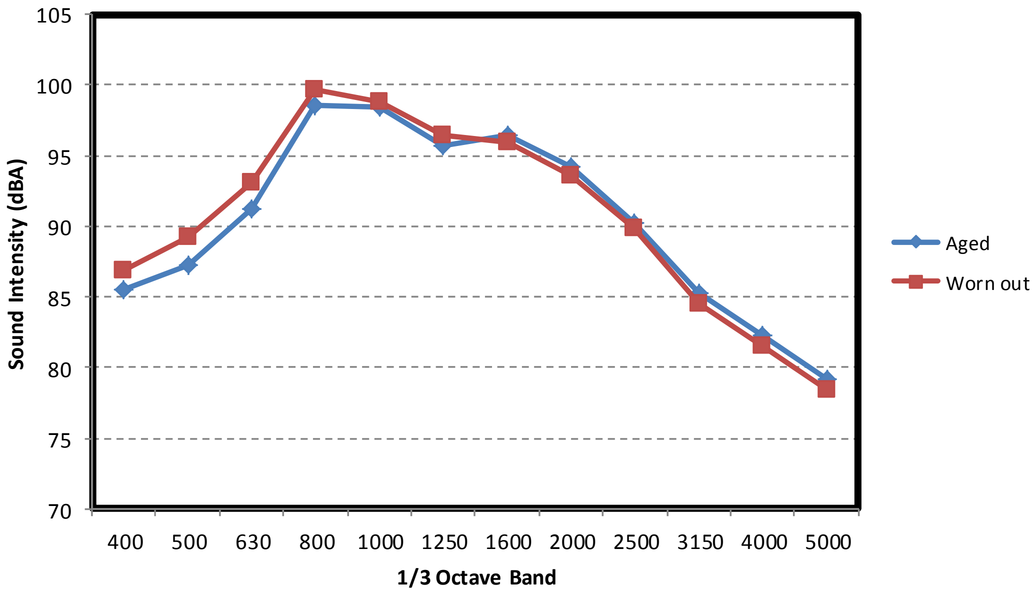


Figure 3.3: Comparison of average OBSI spectral content for burlap drag sections with texture in different conditions.

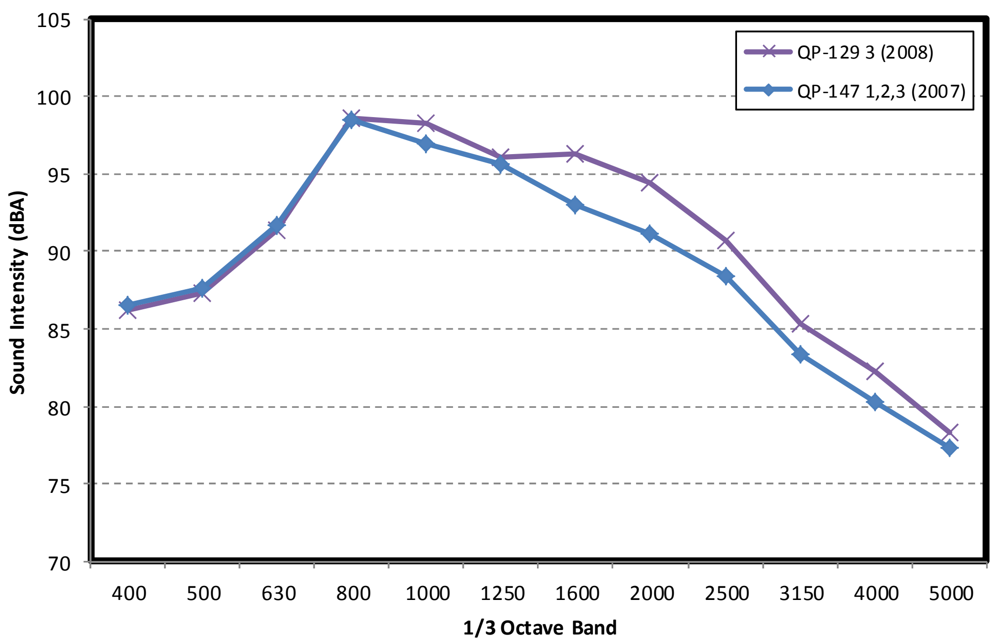


Figure 3.4: OBSI spectral content for diamond-ground sections, texture *new.*

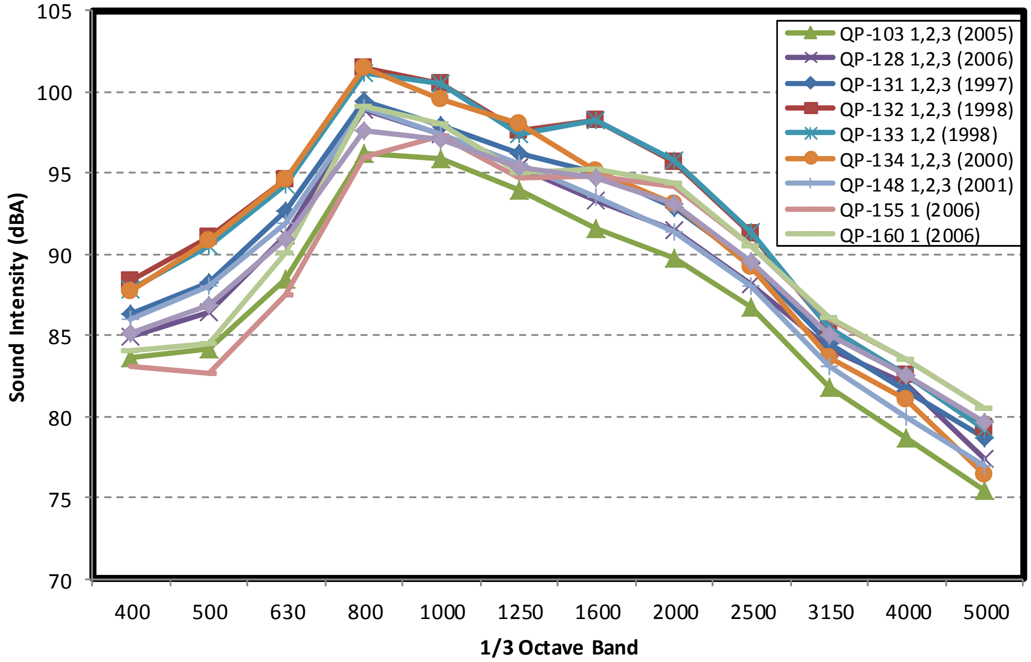


Figure 3.5: OBSI spectral content for diamond-ground sections, texture *aged.*

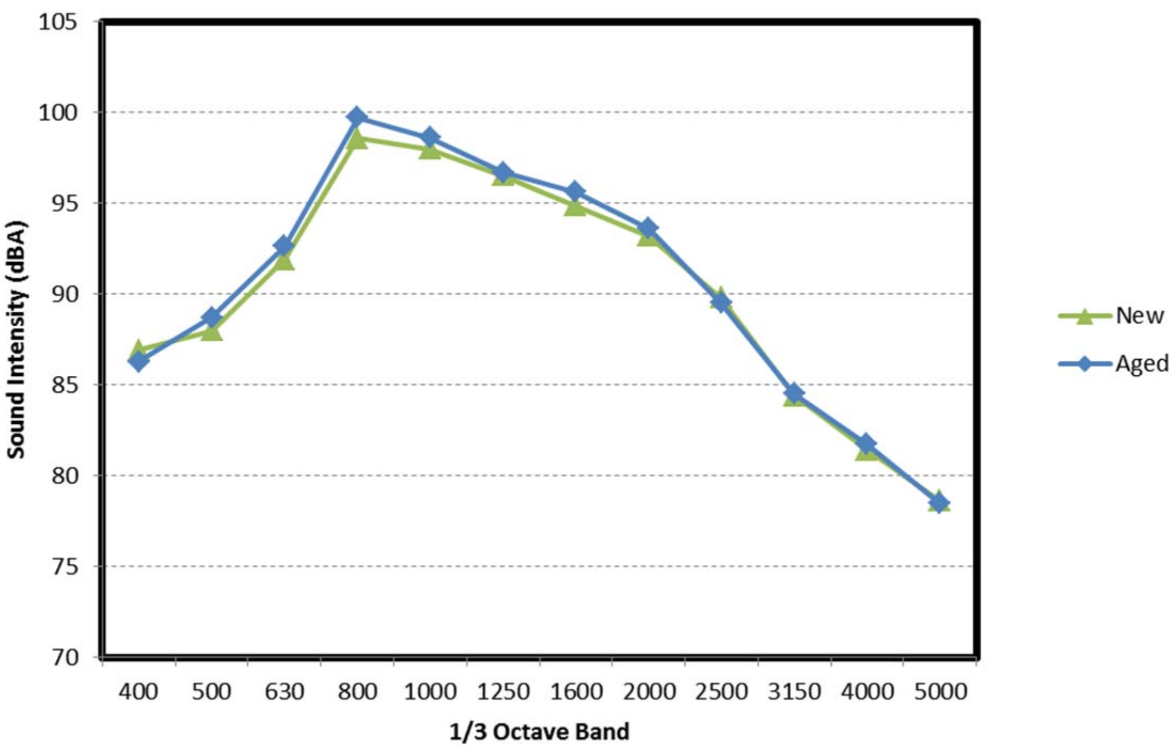


Figure 3.6: Comparison of OBSI spectral content for diamond-ground sections with texture in different conditions.

3.1.3 Diamond-Grooved Sections

All diamond-grooved sections fall in the *aged* texture category. Figure 3.7 shows the results at each site. There is a peak at about 800 Hz and range of 4 to 5 dBA for every frequency within the *aged* texture category.

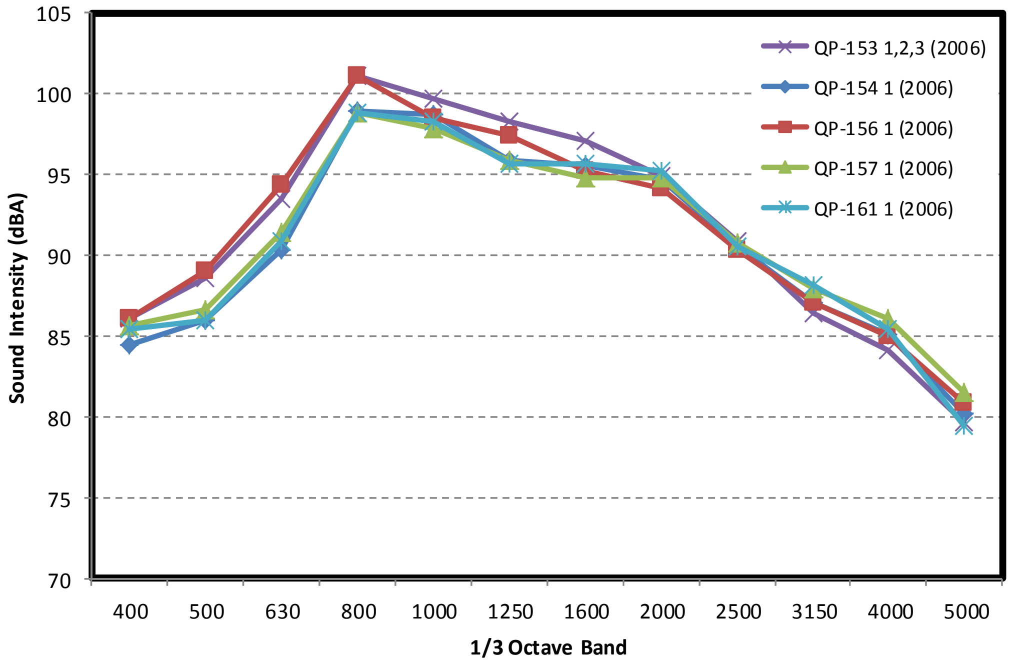


Figure 3.7: OBSI spectral content for diamond-grooved sections, texture *aged*.

3.1.4 Longitudinally Broomed Sections

There were no sections with longitudinally broomed texture in the *new* and *worn out* texture categories. The OBSI levels of the texture *aged* sections are shown in Figure 3.8. It can be seen that the newer section (QP-162) exhibits higher noise levels in the high frequency region.

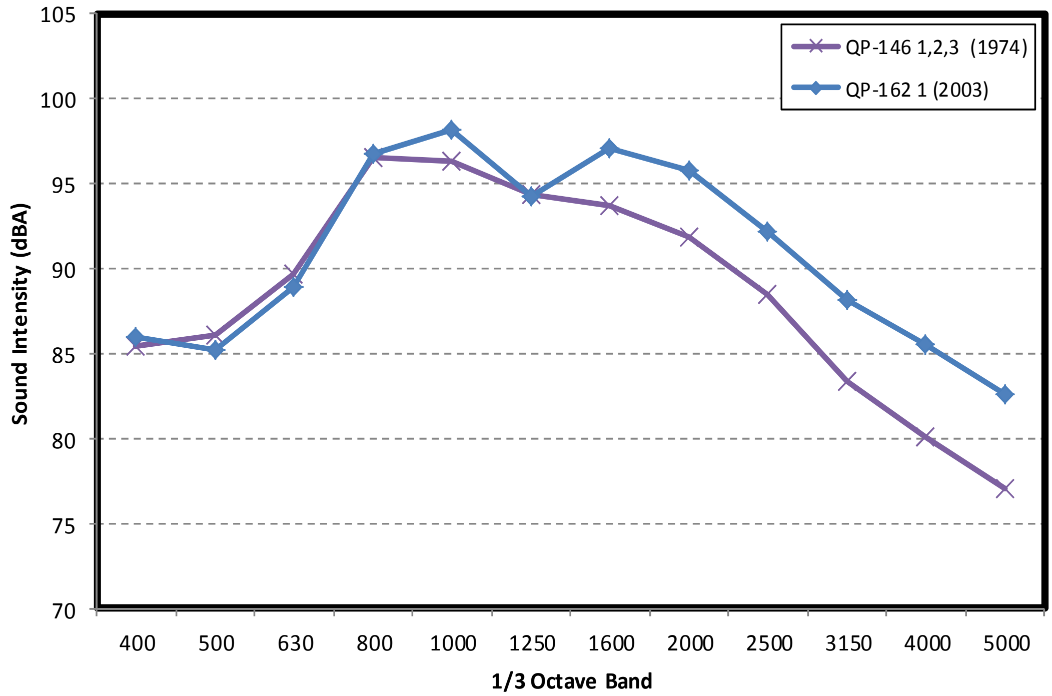


Figure 3.8: OBSI spectral content for longitudinally broomed sections, texture *aged.*

3.1.5 Longitudinally Tined Sections

This is the only texture type with sections found in the three texture conditions, although there is only one *new* section and one *worn out* section. Sections with longitudinally tined texture in the *aged* texture category are presented in Figure 3.9. The data from Section QP-142 were excluded from the analysis because of extensive damage to the pavement surface caused by truck chain wear. The average spectra for the *aged* longitudinally tined sections have relatively consistent shapes and values across the different sections compared with the other types of textures. A comparison of the average spectral content for the conditions is shown in Figure 3.10.

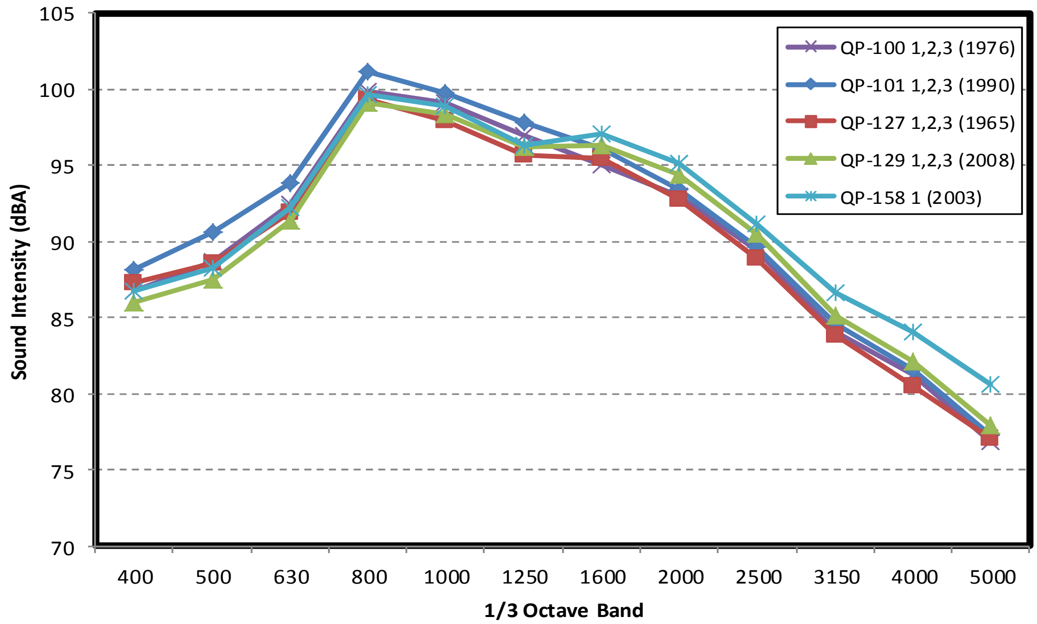


Figure 3.9: OBSI spectral content for longitudinally tined sections, texture *aged.*

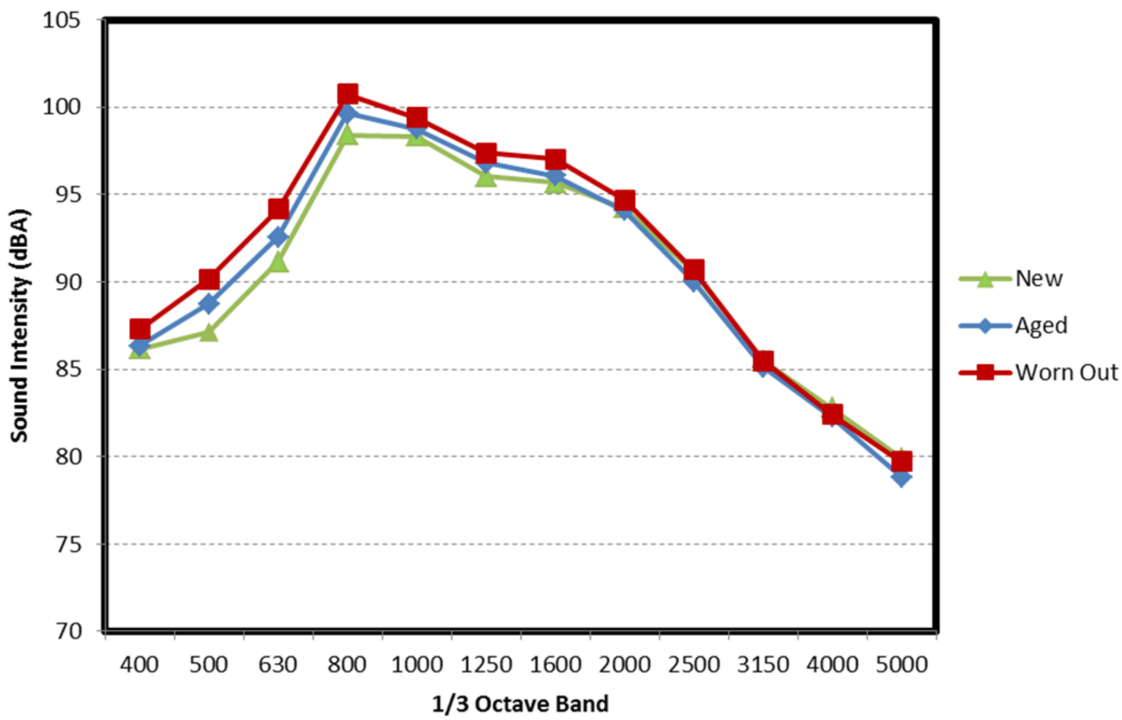


Figure 3.10: Comparison of OBSI spectral content for longitudinally tined sections with texture in different conditions.

3.1.6 Comparison of Textures

For the comparison of textures in this section of the report, data was averaged across all three years of measurement and all sections of each texture type. All the averaged values discussed in this chapter only include those sections for which three years of measurements were available. Also, it was considered appropriate to take into account only those sections with *aged* and *new* texture given the fact that once the texture of a surface has disappeared, its original type is no longer valid. The resulting comparisons are presented in Figure 3.11 to Figure 3.14 for the *aged* and *new* texture categories.

The OBSI spectra results for *aged* textures shown in Figure 3.12 are summarized in Table 3.1. Figure 3.11 and Figure 3.12 show that for the *aged* textures, the average values of the spectra have similar shapes, with exceptions appearing in the small sample of longitudinally broomed textures, which has markedly lower noise levels at frequencies below 1,600 Hz, and in the diamond-grooved texture, which exhibits higher noise levels at frequencies of 3,150 Hz and higher. A majority of the pavement textures have peak OBSI values at around 800 Hz. This is due in part to the A-weighting system which weights frequencies near 1,000 Hz the most in order to reflect 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 (not with the texture characteristics of the pavement surface), with 800 to 1,000 Hz typically being the frequency range associated with tread block noise at 60 mph. Table 3.2 shows the peak sound intensities and corresponding frequencies for all new and aged sections.

Figure 3.12 shows that longitudinally tined and diamond-grooved (small sample) textures have similar variability of OBSI across all frequencies. For the longitudinally tined sections, which has the larger sample size of the two, this indicates that although there may be variation in the texture condition it does not change the overall shape of the spectra much—although the magnitude is different. The diamond-ground texture, of which there is also a larger sample size than of diamond grooved, also shows high variability across the spectrum compared with the longitudinally tined texture. This suggests that the characteristics of the diamond-ground surfaces that contribute to the variability across the spectrum should be further investigated in the next year of testing.

Figure 3.13 and Figure 3.14 show that among the relatively small number of sections with *new* texture, sections with longitudinal tining have slightly lower OBSI values at frequencies below 800 Hz and higher OBSI values at frequencies greater than 800 Hz compared with sections with diamond-ground texture. Figure 3.14 shows that the diamond-ground sections have relatively high variability for noise levels at frequencies of 1,000 Hz and higher, while the noise levels of longitudinally tined sections vary more around 1,000 Hz and 1,250 Hz with low variability at other frequencies. These results indicate that more detailed investigation of the characteristics of *new* DG and LT sections may provide more insight into the reasons for these differences in variability.

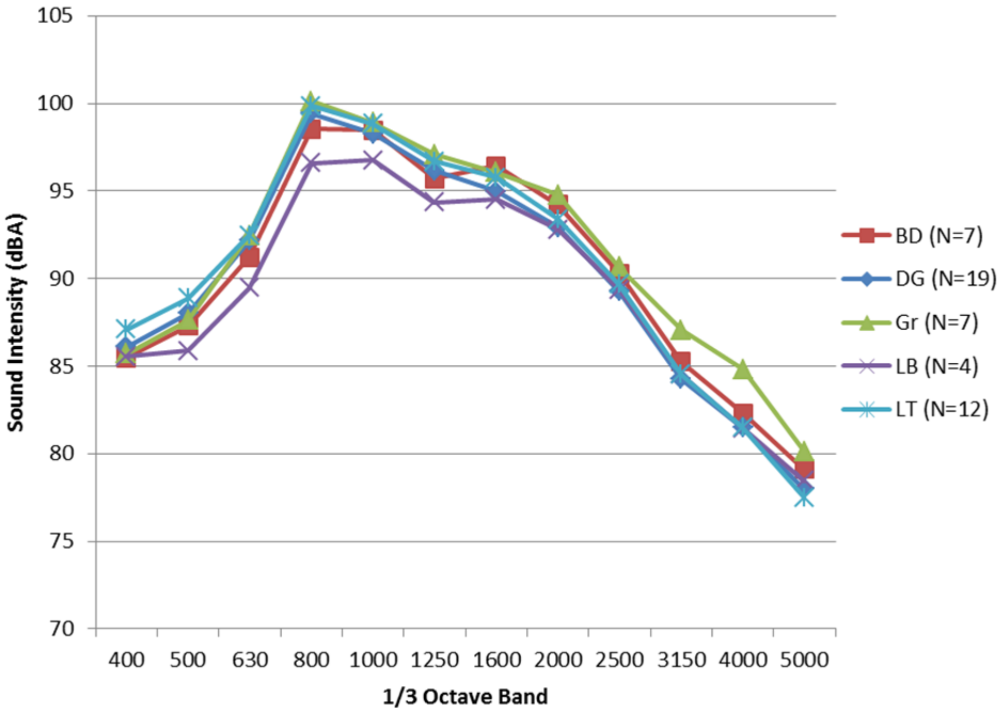


Figure 3.11: Comparison of OBSI spectral content of sections with different texture types, average of sections with texture *aged.*
(Note: BD = burlap drag, DG=diamond ground, Gr=diamond grooved, LB = longitudinally broomed, LT = longitudinally tined; numbers in parentheses indicate the number of sections at each year of data collection.)

The minimum and maximum OBSI spectra values for the one-third octaves are shown for all sections with *aged* texture in Figure 3.15 and Figure 3.16, respectively. The minimum curve is the minimum OBSI value measured at each frequency from all of the sections with a given texture, with the maximum curve being the same for the maximum value at each frequency. It can be seen in Figure 3.15 that the diamond-ground texture shows the minimum of all minimum values over most of the frequency spectrum. This value reflects how low the noise level of one section with a specified texture can be. Sections with longitudinal tining exhibited the highest minimum values among all the texture types at frequencies less than 1,000 Hz, while the sections with diamond-grooved texture had the highest minimum levels at frequencies above 2,000 Hz. It can be seen in Figure 3.16 that the diamond-ground texture had the highest maximums for frequencies of 2,000 Hz and lower, and the quietest maximums at frequencies above 2,000 Hz. Diamond-grooving had the highest maximum for frequencies above 2,000 Hz.

The diamond-ground, diamond-grooved, and longitudinally tined textures all have longitudinal directionality, with the differences among the texture types being the width and depth of the channels and the plateaus between the channels, as well as the shape of the edges of the plateaus. Measurement of the actual shapes and dimensions of the longitudinal directionality may provide insight into the variability within and between these textures.

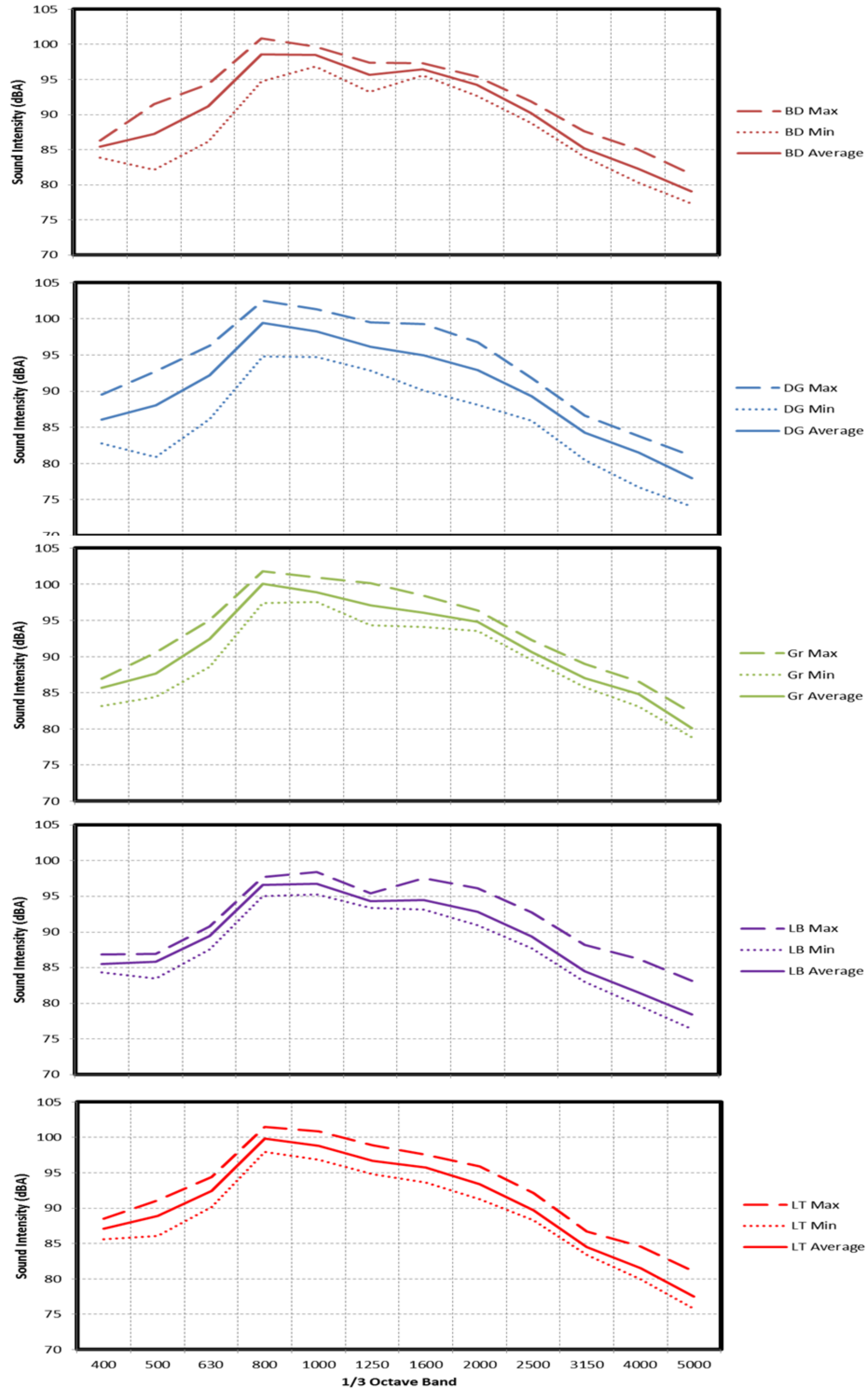


Figure 3.12: Comparison of OBSI spectral content of sections of different texture types (only texture *aged).*

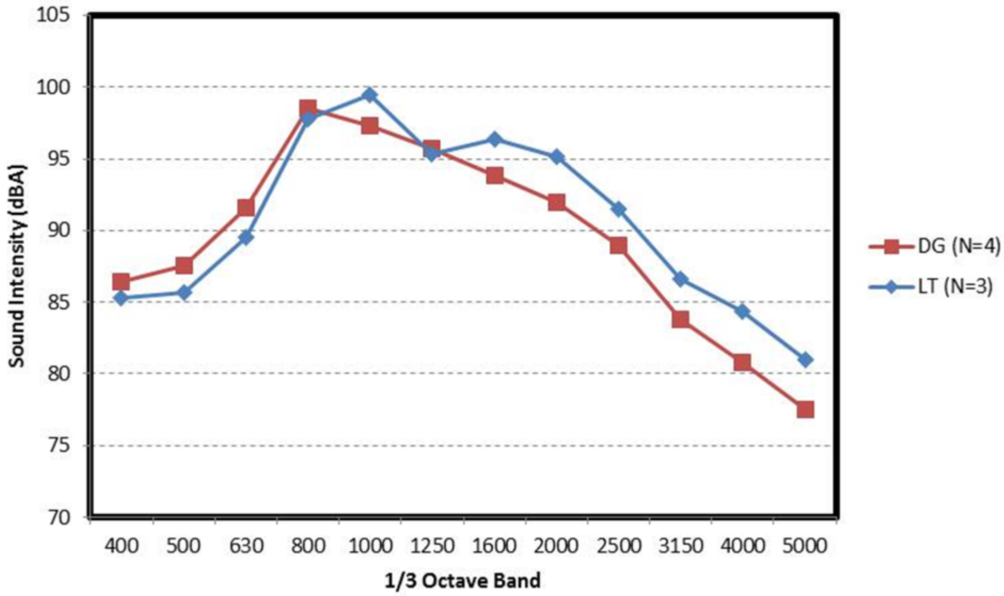


Figure 3.13: Comparison of OBSI spectral content of sections with different texture types, average of sections with texture *new.*
(Note: DG = diamond ground and LT = longitudinally tined; numbers in the parentheses indicate the number of sections at each year of data collection.)

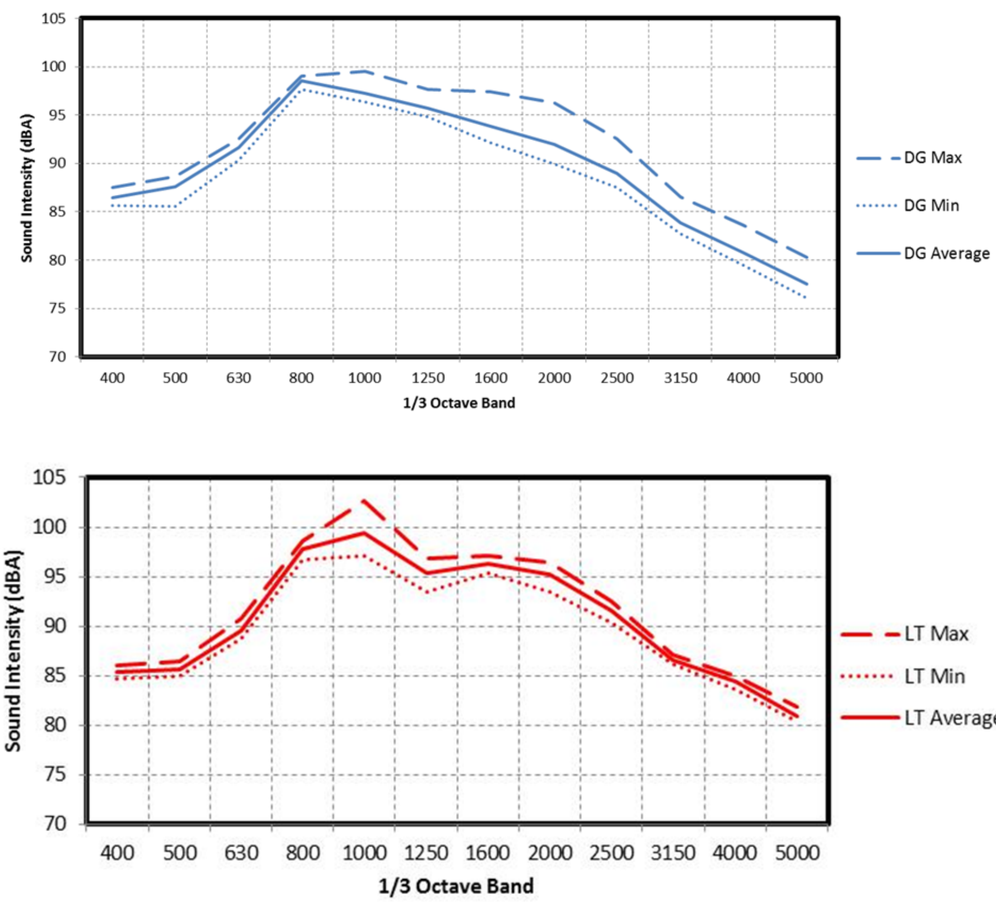


Figure 3.14: Comparison of OBSI spectral content of sections of different texture types (only texture *new).*

Table 3.1: Sound Intensity in One-Third Octaves of Sections with Texture *Aged* (for sections with three years of measurements)

		400	500	630	800	1,000	1,250	1,600	2,000	2,500	3,150	4,000	5,000	Overall
BD	Max.	86.3	91.5	94.4	100.8	99.7	97.4	97.3	95.4	91.9	87.6	85.1	81.5	105.9
	Avg.	85.5	87.3	91.2	98.5	98.5	95.7	96.4	94.2	90.3	85.2	82.3	79.1	104.3
	Min.	83.9	82.2	86.2	94.7	96.9	93.2	95.6	92.7	88.8	84.0	80.4	77.3	101.9
DG	Max.	89.5	92.8	96.3	102.5	101.4	99.6	99.3	96.7	91.8	86.6	83.8	81.1	107.5
	Avg.	86.1	88.0	92.2	99.4	98.3	96.2	95.0	92.9	89.3	84.3	81.5	78.0	104.6
	Min.	82.7	80.9	86.1	94.8	94.7	92.8	90.1	88.1	85.9	80.5	76.7	74.0	101.2
Gr	Max.	86.9	90.6	95.0	101.8	101.0	100.1	98.5	96.4	92.3	89.0	86.5	82.2	107.6
	Avg.	85.7	87.6	92.5	100.1	98.9	97.1	96.1	94.8	90.7	87.0	84.8	80.1	104.8
	Min.	83.2	84.4	88.6	97.4	97.6	94.3	94.1	93.6	89.6	85.7	83.0	78.8	102.1
LB	Max.	86.9	87.0	90.8	97.7	98.4	95.5	97.6	96.1	92.8	88.2	86.2	83.1	104.4
	Avg.	85.6	85.9	89.5	96.6	96.8	94.4	94.5	92.8	89.4	84.5	81.5	78.4	102.5
	Min.	84.3	83.5	87.6	95.0	95.3	93.4	93.2	91.0	87.7	83.0	79.7	76.4	101.1
LT	Max.	88.5	91.1	94.4	101.5	100.9	98.9	97.5	95.9	92.1	86.7	84.6	81.0	106.8
	Avg.	87.1	88.9	92.5	99.9	98.8	96.7	95.8	93.4	89.7	84.5	81.5	77.5	105.0
	Min.	85.6	86.1	90.1	97.9	96.9	94.8	93.7	91.3	88.3	83.4	79.9	75.8	103.1

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.

Table 3.2: Maximum Sound Intensity in One-Third Octaves of Sections and Corresponding Frequencies

Section ID	Texture	Texture Condition	Year 1		Year 2		Year 3	
			Peak OBSI	Freq.@Peak	Peak OBSI	Freq.@Peak	Peak OBSI	Freq.@Peak
QP-123.1	BD	Aged	99.4	800	100.1	800	100.8	800
QP-123.3	BD	Aged	98.9	800	99.1	800	99.9	800
QP-123.2	BD	Aged	99.0	800	99.0	800	99.7	800
QP-115.2	BD	Aged	98.5	800	99.5	1,000	99.2	800
QP-115.1	BD	Aged	98.9	800	99.7	1,000	99.0	1,000
QP-115.3	BD	Aged	98.1	800	99.6	1,000	98.7	1,000
QP-159.1	BD	Aged	97.8	1,000	98.0	1,000	98.2	1,000
QP-126.3	BD	Worn off	102.8	800	102.6	800	103.8	800
QP-126.1	BD	Worn off	103.3	800	102.9	800	103.6	800
QP-116.1	BD	Worn off	101.9	800	103.0	800	102.7	800
QP-116.2	BD	Worn off	101.9	800	102.6	800	102.7	800
QP-104.3	BD	Worn off	100.6	800	100.1	800	102.6	800
QP-130.1	BD	Worn off	102.0	800	102.6	800	102.5	800
QP-130.2	BD	Worn off	101.2	800	102.5	800	102.2	800
QP-126.2	BD	Worn off	100.9	800	100.9	800	102.2	800
QP-104.2	BD	Worn off	100.0	800	99.9	800	102.0	800
QP-116.3	BD	Worn off	101.4	800	102.3	800	101.9	800
QP-104.1	BD	Worn off	99.5	800	99.3	800	101.6	800
QP-130.3	BD	Worn off	102.1	800	102.4	800	101.6	800
QP-105.2	BD	Worn off	99.3	800	99.3	800	101.6	800
QP-105.3	BD	Worn off	98.7	800	99.0	1,000	101.5	800
QP-105.1	BD	Worn off	98.7	800	99.2	1,000	101.3	800
QP-107.1	BD	Worn off	97.7	1,000	99.4	1,000	99.4	800
QP-106.2	BD	Worn off	97.7	800	98.5	1,000	99.0	1,000
QP-106.3	BD	Worn off	97.8	800	98.4	1,000	98.7	1,000
QP-106.1	BD	Worn off	97.0	800	98.4	1,000	98.6	1,000
QP-107.3	BD	Worn off	97.2	1,000	99.2	1,000	98.6	800

Section ID	Texture	Texture Condition	Year 1		Year 2		Year 3	
			Peak OBSI	Freq.@Peak	Peak OBSI	Freq.@Peak	Peak OBSI	Freq.@Peak
QP-107.2	BD	Worn off	97.1	1,000	99.0	1,000	98.4	1,000
QP-102.1	BD	Worn off	96.5	1,000	98.0	1,000	97.9	1,000
QP-102.3	BD	Worn off	96.2	1,000	98.0	1,000	97.5	1,000
QP-102.2	BD	Worn off	96.1	1,000	97.9	1,000	97.4	1,000
QP-134.1	DG	Aged	101.4	800	102.3	800	102.5	800
QP-132.2	DG	Aged	101.4	800	102.0	800	102.4	800
QP-132.3	DG	Aged	100.6	800	101.5	800	102.2	800
QP-134.3	DG	Aged	101.9	800	102.1	800	102.0	800
QP-132.1	DG	Aged	100.6	800	100.8	800	101.7	800
QP-133.1	DG	Aged	101.1	800	100.8	800	101.4	800
QP-134.2	DG	Aged	100.5	800	99.8	800	101.0	800
QP-128.2	DG	Aged	99.1	800	99.1	800	99.7	800
QP-160.1	DG	Aged	99.6	800	98.1	1,000	99.7	800
QP-128.1	DG	Aged	99.4	800	99.5	800	99.7	800
QP-148.1	DG	Aged	99.1	800	97.9	800	99.6	800
QP-148.2	DG	Aged	99.2	800	98.6	800	99.6	800
QP-131.3	DG	Aged	101.2	800	98.4	800	99.6	800
QP-148.3	DG	Aged	99.3	800	98.5	800	99.4	800
QP-131.2	DG	Aged	100.4	800	98.3	800	99.1	800
QP-131.1	DG	Aged	101.0	800	98.4	800	99.0	800
QP-166.1	DG	Aged	97.8	800	97.6	1,000	97.9	800
QP-128.3	DG	Aged	97.5	800	97.6	800	97.8	800
QP-155.1	DG	Aged	97.3	1,000	97.2	1,000	97.2	1,000
QP-129.3	DG	New	98.8	800	98.6	1,000	99.5	1,000
QP-147.2	DG	New	99.0	800	98.3	800	98.9	800
QP-147.3	DG	New	98.9	800	98.0	800	98.7	800
QP-147.1	DG	New	98.9	800	98.2	800	97.7	800
QP-153.3	Gr	Aged	101.0	800	101.3	800	101.8	800
QP-156.1	Gr	Aged	100.5	800	101.2	800	101.4	800
QP-153.2	Gr	Aged	101.1	800	100.9	800	101.2	800

Section ID	Texture	Texture Condition	Year 1		Year 2		Year 3	
			Peak OBSI	Freq.@Peak	Peak OBSI	Freq.@Peak	Peak OBSI	Freq.@Peak
QP-153.1	Gr	Aged	100.2	800	100.9	800	101.0	800
QP-157.1	Gr	Aged	98.2	800	98.6	800	99.8	800
QP-161.1	Gr	Aged	98.9	800	98.6	800	99.1	800
QP-154.1	Gr	Aged	98.3	1,000	101.8	800	97.7	1,000
QP-162.1	LB	Aged	97.8	1,000	98.3	1,000	98.4	1,000
QP-146.1	LB	Aged	96.9	800	97.1	800	97.7	800
QP-146.2	LB	Aged	96.5	800	96.3	1,000	97.3	1,000
QP-146.3	LB	Aged	96.4	800	96.2	1,000	96.9	1,000
QP-100.2	LT	Aged	100.4	800	101.5	800	101.5	800
QP-101.2	LT	Aged	101.3	800	101.0	800	101.4	800
QP-101.3	LT	Aged	100.9	800	101.0	800	101.3	800
QP-101.1	LT	Aged	100.9	800	100.8	800	101.3	800
QP-100.3	LT	Aged	99.0	800	99.8	800	100.2	800
QP-158.1	LT	Aged	99.4	800	99.4	800	100.2	800
QP-127.2	LT	Aged	99.6	800	99.8	800	99.9	800
QP-100.1	LT	Aged	98.0	800	99.7	1,000	99.6	800
QP-127.3	LT	Aged	98.8	800	98.8	800	99.5	800
QP-129.2	LT	Aged	99.0	800	98.8	1,000	99.5	1,000
QP-127.1	LT	Aged	98.6	800	99.2	800	99.3	800
QP-129.1	LT	Aged	99.2	800	98.9	800	99.2	800
QP-117.2	LT	New	97.4	1,000	102.6	1,000	98.9	1,000
QP-117.1	LT	New	97.4	1,000	102.0	1,000	98.9	1,000
QP-117.3	LT	New	97.4	800	102.3	1,000	98.6	1,000
QP-108.2	LT	Worn off	101.3	800	102.9	800	103.0	800
QP-108.3	LT	Worn off	101.2	800	102.4	800	102.9	800
QP-108.1	LT	Worn off	101.1	800	102.4	800	102.6	800

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.

Average noise spectra for the *aged* and *new* conditions for each texture type across the three years of measurement are shown in Appendix D. Overall, small incremental increases in noise levels were seen across nearly all textures and frequencies.

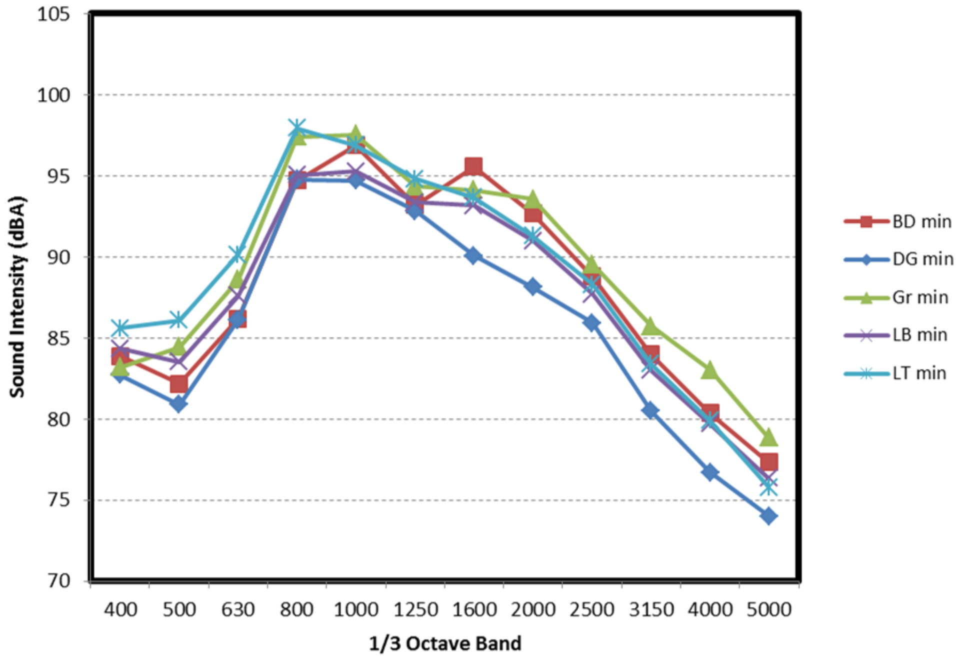


Figure 3.15: Comparison of OBSI spectral content of sections with different texture types, minimum of sections with *aged* texture.
(Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.)

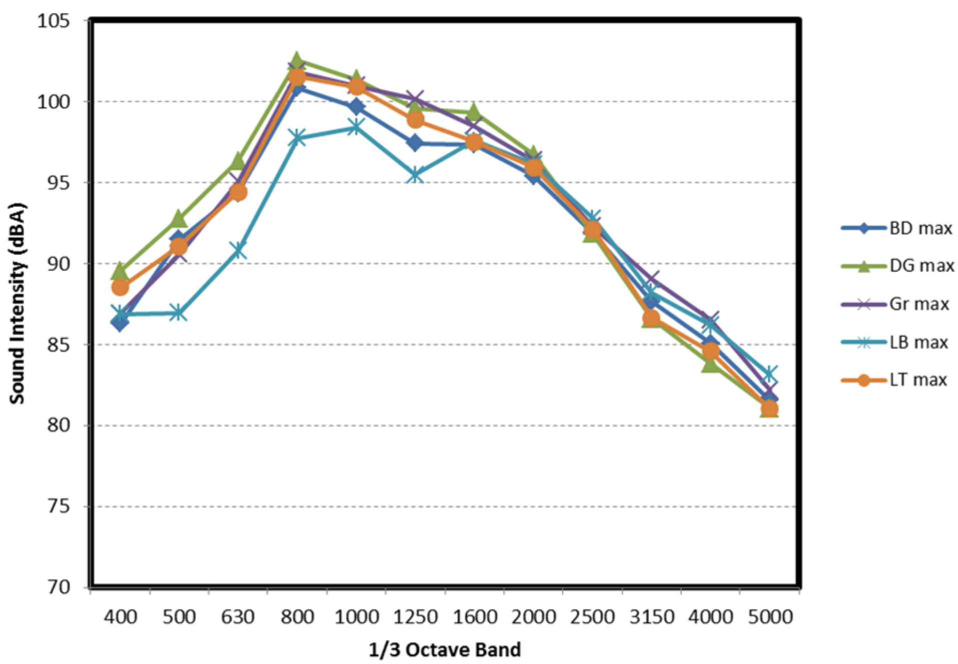


Figure 3.16: Comparison of OBSI spectral content of sections with different texture types, maximum of sections with *aged* texture.
(Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.)

3.2 Overall Sound Intensity

The overall OBSI measurements for sections in the both the *new* and *aged* conditions together are presented by surface type using box plots in Figure 3.17. The box plots show the minimum and the maximum values, as well as the mean and the 1st and 3rd quartiles. Almost all texture types exhibited a year-to-year increase in sound intensity. Each texture type and the details of the overall OBSI level of each section measured in Years 1, 2, and 3 appear in Appendix A.

Figure 3.18 shows the average overall OBSI values for sections with *new* textures. Figure 3.19 shows average overall OBSI values for sections with *aged* textures. It can be seen that there is a general trend of increasing overall OBSI over the three years. Figure 3.20 and Figure 3.21 show the three-year average overall OBSI results for different texture types for the *aged* and *worn out* texture conditions, respectively.

The mean results for overall OBSI by surface type along with standard deviations for each texture condition are presented in Table 3.3. Table 3.4 presents the same information, but only for *new* and *aged* textures; that is, the sections with *worn out* texture have been excluded. It can be seen that separating out the texture *worn out* sections did not have much effect on the mean overall OBSI levels. These results indicate that using visual observation to categorize texture condition either fails to capture the texture condition in terms of degradation from traffic and the environment, or that there are other characteristics besides traffic degradation (i.e., the wearing down of the texture) which have an even stronger influence on tire/pavement noise. This suggests that detailed measurements of the textures should be made in the next year of testing in order to try to better understand the effects of texture characteristics on noise.

Based on the results shown in Table 3.4 and Figure 3.20 and Figure 3.21, which contain averaged data from all three years and consider the mean OBSI results for all sections that have the same nominal surface type with *new* and *aged* texture conditions, the quietest texture type was found to be the longitudinally broomed (LB).

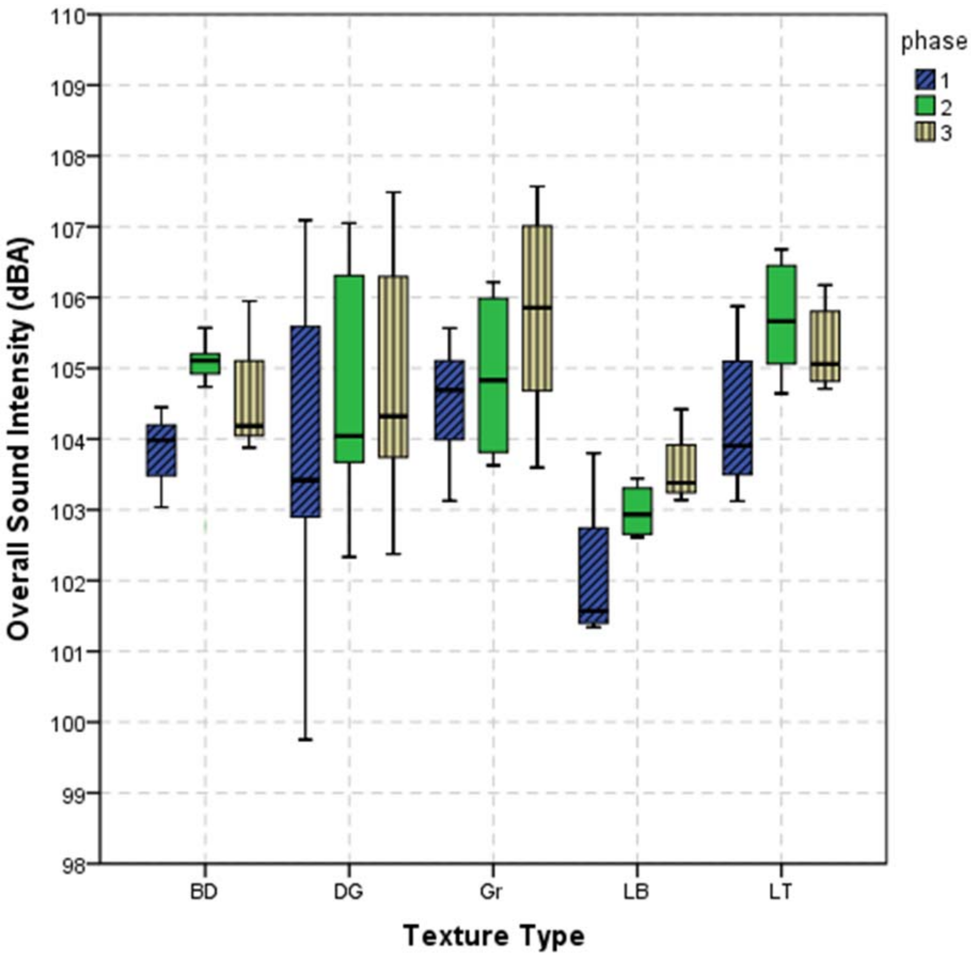


Figure 3.17: Box plots of OBSI results by texture type, all measurements from Years 1, 2, and 3, with *new* and *aged* conditions.
(Notes: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, and LT = longitudinally tined.)

This conclusion, however, must be treated with caution because of the small sample size for this texture type. As seen in Table 3.4, the longitudinally broomed group presented a mean OBSI level of 102.5 dBA based on 12 measurements obtained by combining the three years of results on four sections located at two different sites. Also, the difference between the longitudinally broomed and burlap drag surface textures is only clear on surfaces that are not *worn out* and still show the striations caused by the texturing tool. In this study, the presence of striations of more than 1 or 2 mm depth (as evaluated subjectively from photographs) was considered enough texture to label a texture as longitudinally broomed. If only shallower striations or none were observed, then the section was labeled as having the burlap drag texture type. This resulted in a low number of longitudinally broomed sections, which unbalanced the experiment, and in turn made any interpretation of the results more complicated. From a practical point of view, longitudinal brooming can be considered equivalent to a "heavy drag" texture.

Next, the burlap drag and diamond-ground texture types showed values similar to each other in terms of mean OBSI level—104.3 and 104.4 dBA, respectively—and are therefore ranked as the second quietest. The value for diamond-ground sections is based on 69 measurements obtained by averaging the three years of results on 23 sections located at 11 different sites. For burlap drag the value is the result of 21 measurements obtained by averaging the three years of results on seven sections located at three different sites. Diamond-grooved and longitudinally tined surfaces had mean OBSI levels of 104.8 dBA and 104.9 dBA, respectively. There were 21 measurements at five different sites for diamond grooved, and 45 measurements at six sites for longitudinally tined surfaces. These results show that the mean values for overall OBSI are very similar for the burlap drag, diamond-ground, diamond-grooved, and longitudinally tined textures in this sample.

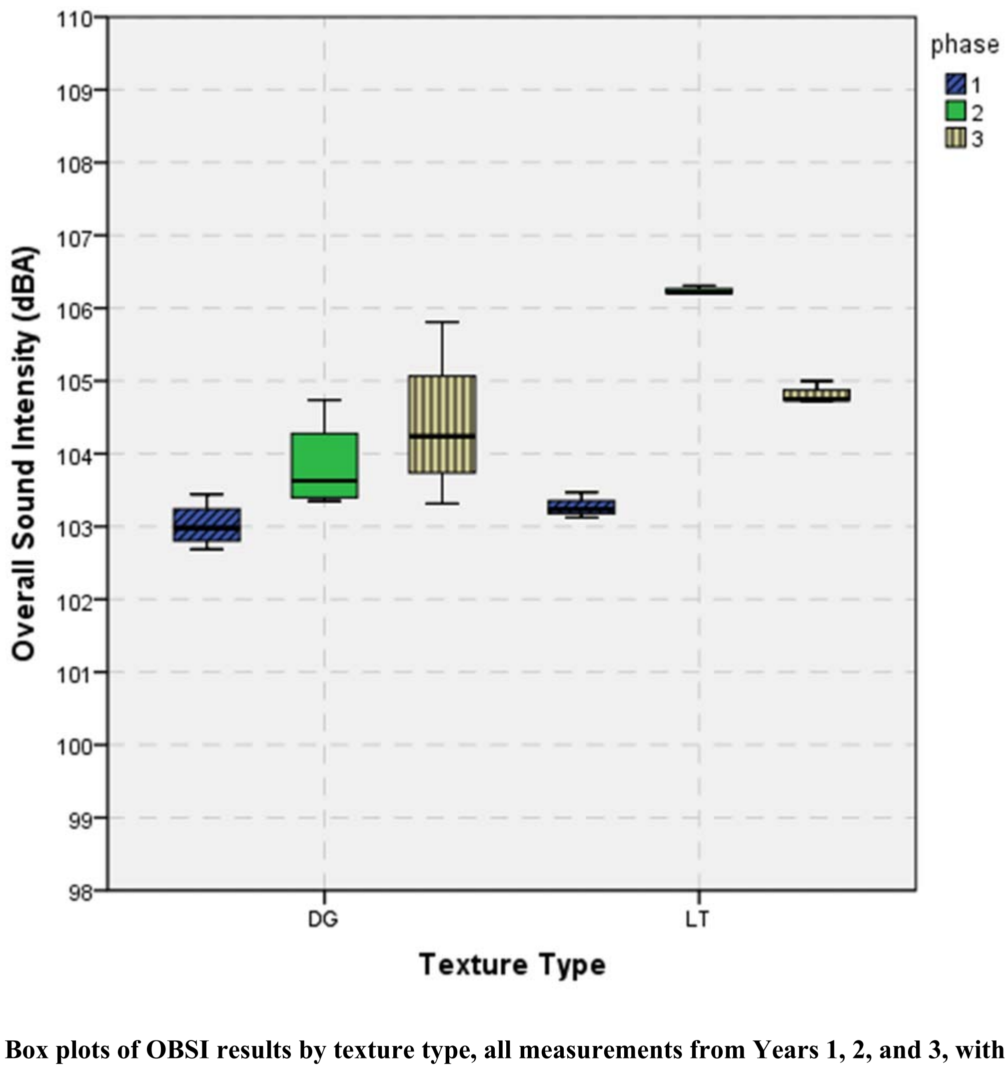


Figure 3.18: Box plots of OBSI results by texture type, all measurements from Years 1, 2, and 3, with *new* condition. (Notes: DG = diamond ground, LT = longitudinally tined.)

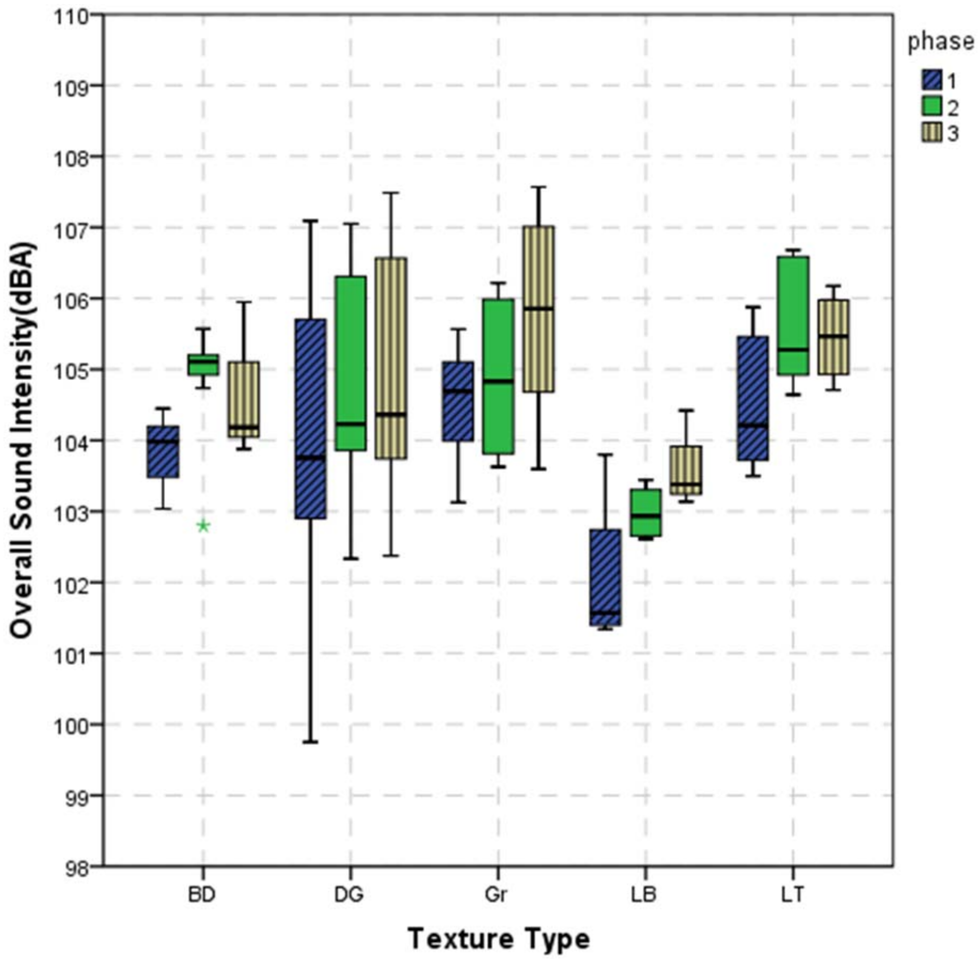


Figure 3.19: Box plots of OBSI results by texture type, all measurements from Years 1, 2, and 3, with *aged* condition.
(Notes: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, and LT = longitudinally tined.)

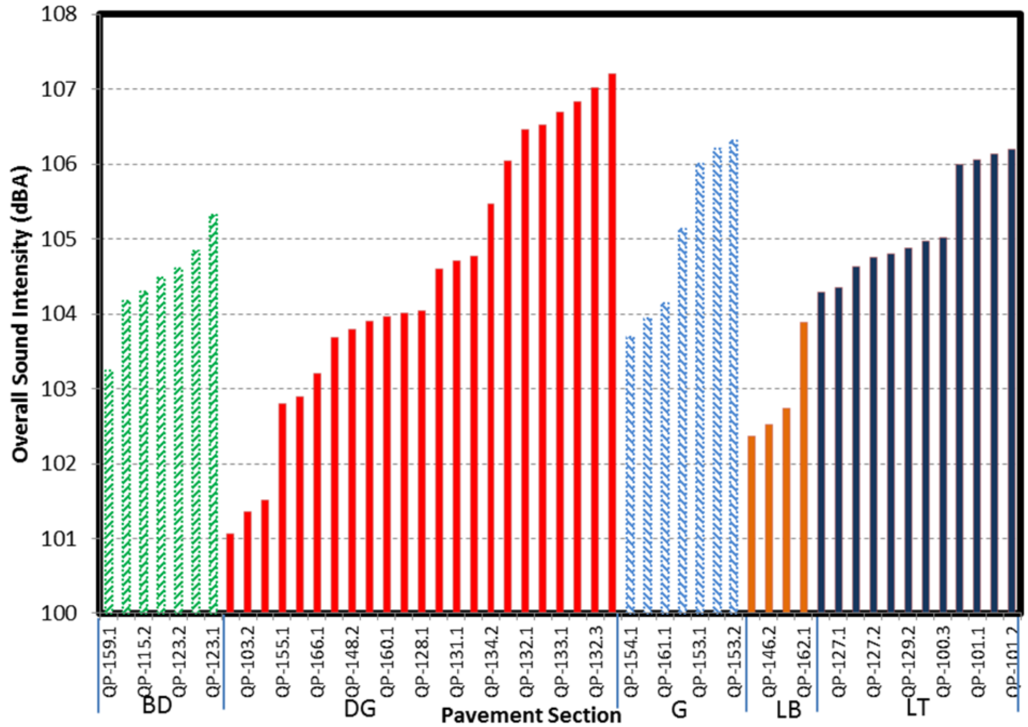


Figure 3.20: Averaged Year 1, 2, and 3 results for the *aged* texture condition for all texture types.
(Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.)

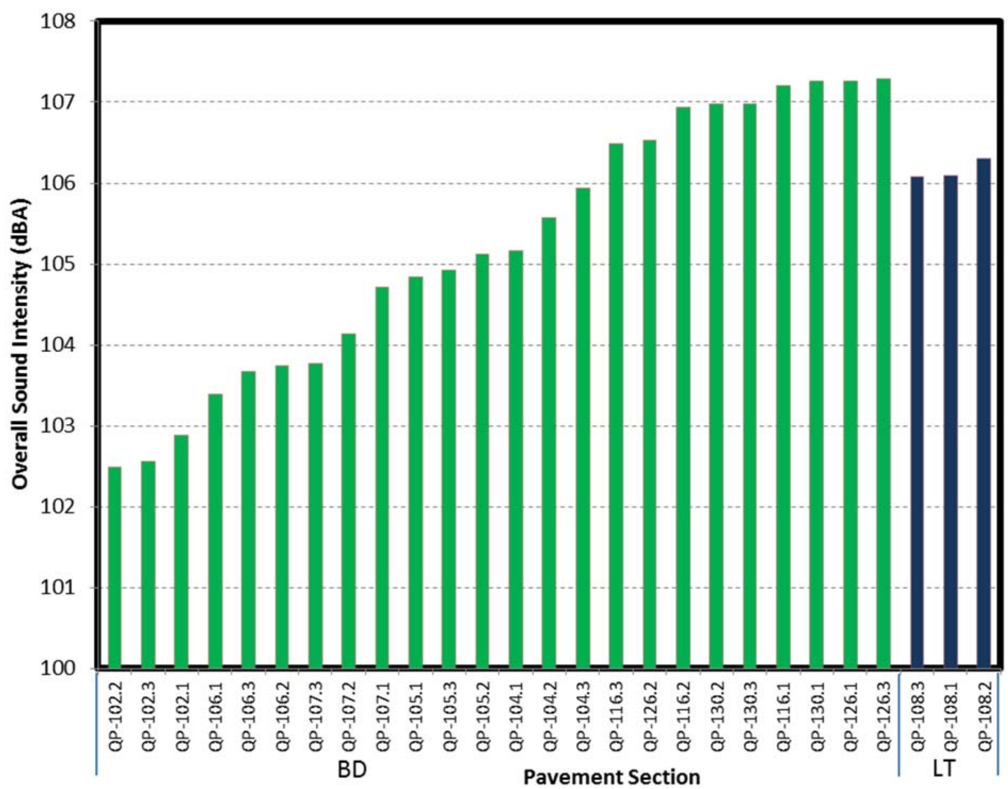


Figure 3.21: Averaged three-year results for the *worn out* texture condition for BD and LT texture types.
(Note: BD = burlap drag, LT = longitudinally tined.)

Table 3.3: Mean Values of Overall OBSI Levels (dBA) by Surface Texture Type and Texture Condition: *New, Aged, Worn Out*

Tex.	Year 1														
	New					Aged					Worn Out				
	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.
BD						7	103.8	.5	103.0	104.4	24	104.4	2.1	101.2	107.3
DG	4	103.0	0.3	102.7	103.4	22	104.0	2.2	99.7	107.1					
Gr						7	104.5	0.9	103.1	105.6					
LB						4	102.1	1.2	101.3	103.8					
LT	3	103.3	.2	103.1	103.5	12	104.5	0.9	103.5	105.9	3	106.0	.4	105.6	106.3
Tex.	**Year 2**														
	New					Aged					Worn Out				
	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.
BD						7	104.8	.9	102.8	105.6	24	105.4	1.4	103.4	107.5
DG	4	103.8	0.6	103.3	104.7	20	104.8	1.5	102.3	107.1					
Gr						7	104.9	1.2	103.6	106.2					
LB						4	103.0	.4	102.6	103.4					
LT	3	106.2	0.1	106.2	106.3	12	105.6	.8	104.6	106.7	3	105.7	.1	105.6	105.8
Tex.	**Year 3**														
	New					Aged					Worn Out				
	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.
BD						7	104.6	.8	103.9	105.9	24	105.9	1.6	102.8	107.6
DG	4	104.4	1.0	103.3	105.8	23	104.9	1.6	102.4	107.5					
Gr						7	105.8	1.5	103.6	107.6					
LB						4	103.6	.6	103.1	104.4					
LT	3	104.8	0.2	104.7	105.0	12	105.4	.6	104.7	106.2	3	106.8	.3	106.5	107.0
Tex.	**Total**														
	New					Aged					Worn Out				
	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.	N	Mean	Std.	Min.	Max.
BD						21	104.4	.8	102.8	105.9	72	105.2	1.8	101.2	107.6
DG	12	103.8	0.9	102.7	105.8	65	104.6	1.8	99.7	107.5					
Gr						21	105.1	1.3	103.1	107.6					
LB						12	102.9	1.0	101.3	104.4					
LT	9	104.8	1.3	103.1	106.3	36	105.2	.9	103.5	106.7	9	106.2	.5	105.6	107.0

Table 3.4: Mean Values of Overall OBSI Levels (dBA) by Surface Texture Type, Only *New* and *Aged* Textures

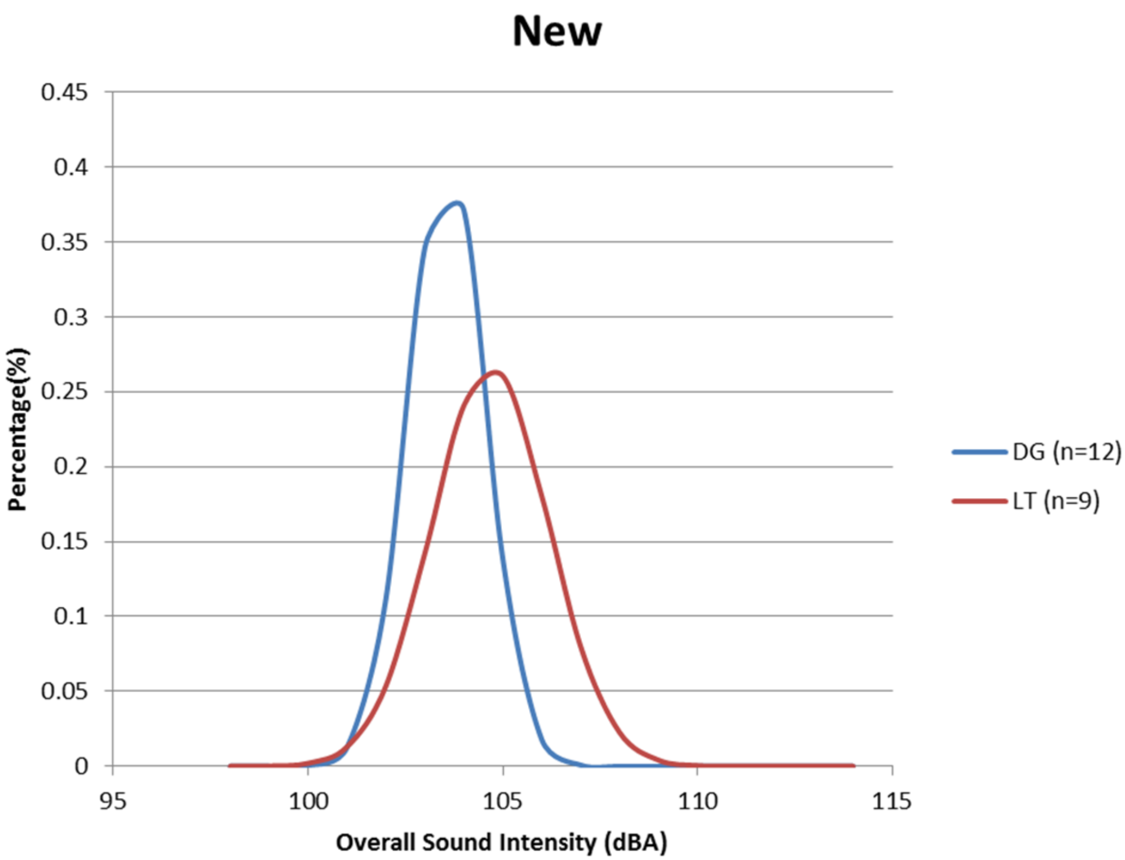
	Year											
	1			2			3			Total		
	Mean	Std. Deviation	N	Mean	Std. Deviation	N	Mean	Std. Deviation	N	Mean	Std. Deviation	N
BD	103.5	0.8	7	104.6	1.1	7	104.6	0.8	7	104.3	21.0	104.3
DG	103.9	1.7	23	104.3	1.6	23	105.0	1.4	23	104.4	69.0	104.4
Gr	103.8	1.5	7	104.7	1.4	7	105.8	1.5	7	104.8	21.0	104.8
LB	101.6	0.6	4	102.5	0.4	4	103.6	0.6	4	102.5	12.0	102.5
LT	103.8	0.9	15	105.7	0.9	15	105.3	0.6	15	104.9	45.0	104.9

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.

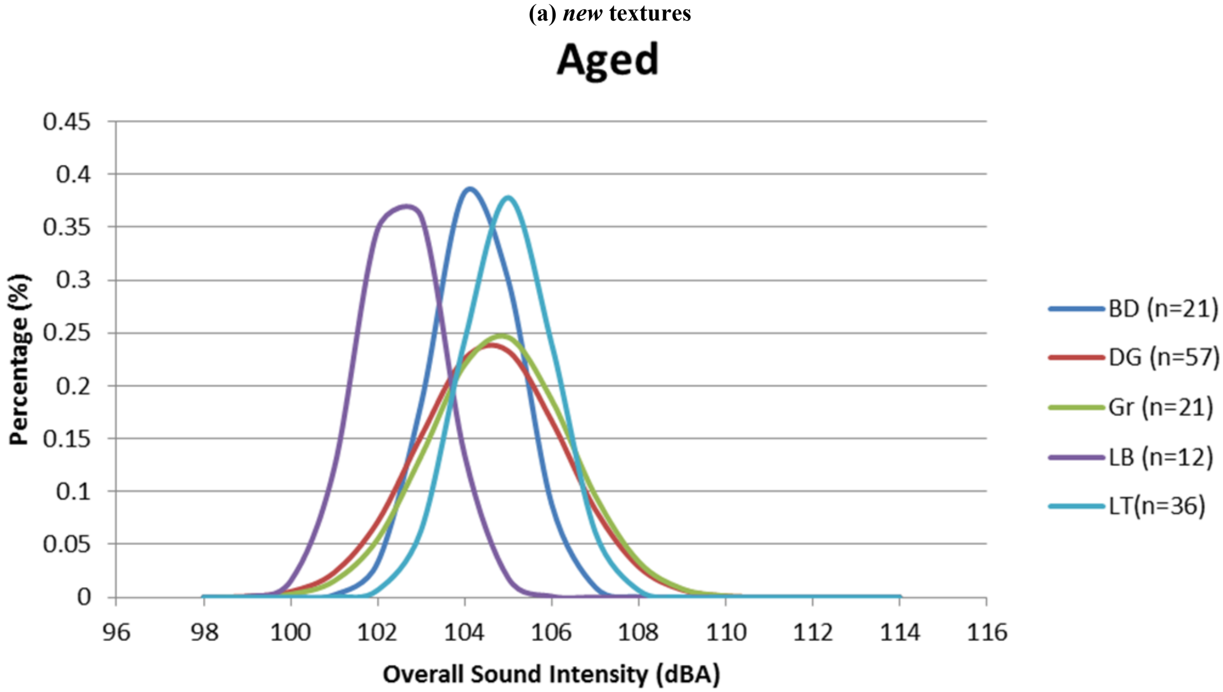
Figure 3.22(a) and (b) show normal distribution curves for each texture type and for the *new* and *aged* texture conditions, respectively. These curves were prepared using the mean and standard deviation of OBSI levels that were presented in Table 3.4 for the combined data from Years 1, 2, and 3 for each texture type. The longitudinally tined and diamond-ground textures have the greatest variability, nearly identical distributions for the *aged* texture, and similar distributions for the *new* texture condition. These results again indicate that characteristics of the textures other than nominal type and visual condition category (*new, aged, worn out*) are causing large variations in the overall OBSI values.

The differences in the means of the overall OBSI values shown in Figure 3.22 among the various texture types are fairly small. The largest difference in mean OBSI levels is between the longitudinally broomed (LB) and longitudinally tined (LT) sections, which have a difference of 2.9 dBA in the combined three-year pooled data. Since there are five texture types in the study, evaluating the difference in mean OBSI values among them requires use of 10 combinations of paired textures. A simple two-tailed t-test was used to determine if the difference for each pair is significant or not using the assumed normal distributions.

The significance level adopted was 0.05. The results are presented in Table 3.5. The following is an example interpretation of the analysis based on the table (for the first row, all sections): "The -0.2 dBA difference between the mean OBSI of the burlap drag (BD) and diamond-ground (DG) sections is not significant at the 95 percent confidence level." The significant differences are labeled "Y" (Yes), and others were not found to be significant. A positive difference indicates that the first texture presented a higher mean OBSI than the second one in the comparison. It can be seen that when only *new* and *aged* sections are considered, the mean overall OBSI of LB sections was found to be significantly different from that of BD, DG, Gr, and LT. No other pair-wise comparisons showed a statistically significant difference between the mean overall OBSI values.



(a) *new* textures



(b) *aged* textures

Figure 3.22: Normal distribution curves of OBSI results by texture type, (a) *new* and (b) *aged* texture conditions.

Table 3.5: Difference of Means and Significance Test For Pairs of Texture Types

		Only New and Aged Sections	
Texture 1	**Texture 2**	**Difference (Overall OBSI)**	**Significant?**
BD	DG	-0.2	
BD	Gr	-0.5	
BD	LB	1.1	Y
BD	LT	-0.7	
DG	Gr	-0.4	
DG	LB	1.9	Y
DG	LT	-0.5	
Gr	LB	2.3	Y
Gr	LT	-0.1	
LB	LT	-2.4	Y

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed.

3.3 Results by Texture Type and Age

This section of the report presents the results of OBSI levels by pavement texture type, texture condition (*new, aged, worn out*), and surface age (years since last surfacing). Each of the following charts shows the combined results for Years 1, 2, and 3 for those sections that were tested in all three years.

Figure 3.23 shows OBSI results for the burlap drag sections. Figure 3.24 shows all texture conditions for the burlap drag sections plotted versus the number of years since they were last surfaced, including all Year 1, 2, and 3 measurements. Most of the burlap drag sections are more than 30 years old. The one young section has OBSI values between approximately 103 and 104 dBA during the three years of measurement. Figure 3.25 presents the average overall OBSI level for the burlap drag texture in the different age categories. Sound intensity increased with increases in pavement surface age and condition. For sections older than 40 years, the *worn out* texture had higher sound intensity than the *aged* texture; while for sections 20 to 40 years old, both the *worn out* and *aged* textures had almost the same sound intensity level.

Figure 3.26 shows OBSI results for the diamond-ground sections. Figure 3.27 shows all the texture conditions for the diamond-ground sections plotted versus the number of years since they were last surfaced. It can be seen that the OBSI values were between approximately 102.5 and 106 dBA for measurements on sections less than 10 years old, and that OBSI values were about 1 dBA noisier on the sections between 10 and 14 years old. Figure 3.28 presents the average overall OBSI level for the diamond-ground texture versus the years since last surfacing (age). In general, new diamond-ground textures had slightly higher sound intensities which appear to decrease over 2 to 10 years and then increase after that.

Figure 3.29 shows OBSI results for the diamond-grooved sections. Most of the sections in this category fell in the range of 2.5 to 4.5 years old, and all of the diamond-grooved sections were categorized for texture condition as *aged*. The reader is reminded that texture condition category (*new, aged, worn out*) is based on visual observation of deterioration of the sharp edges caused by the texturing technique, not age (years since last surfacing). Figure 3.30 shows all the texture conditions for the diamond-grooved sections plotted versus the number of years since they were last surfaced. The results show that these sections were initially in the range of approximately 103.5 to 105.5 dBA, and that there was a small increase in overall noise over the three years of measurement.

Figure 3.31 shows OBSI results for the two longitudinally broomed sections that were measured across all three years, both of which have textures in the *aged* condition. The six-year old section is at the Mojave Bypass on State Route 58 (QP-162). The 35-year-old sections are on Interstate 280 in San Mateo County (QP-146). From the very limited available data, it is difficult to draw any conclusions regard the effects of time on this texture type. Figure 3.32 shows the three years of measurements for the two longitudinally broomed sections plotted versus the number of years since they were last surfaced. The newer section had overall OBSI values around 104 dBA, while the older section had values between 101.5 and 103.5 for the three years of measurement.

Figure 3.33 shows OBSI results for the longitudinally tined sections. The OBSI levels remain mostly between 103 and 107 dBA, even for sections that are about 35 to 45 years old. Figure 3.34 shows all the texture conditions (*new, aged, worn out*) for the longitudinally tined sections plotted versus the number of years since they were last surfaced, including all Year 1, 2, and 3 measurements. This figure shows that the overall OBSI of the sections younger than 10 years old is scattered, and that observed texture condition (*new, aged, worn out*) does not appear to predict the overall OBSI. The overall OBSI of the three sections that are older (approximately 20 to 45 years old) indicate a decreasing trend in tire/pavement noise. Figure 3.35 summarizes the average overall OBSI levels for the longitudinally tined texture in different age categories. The results indicate that, when averaged, sections younger than 2 years and older than 10 years are generally quieter than those between 2 and 10 years old.

A comparison across all sections with three years of data showed that the average Year 3 OBSI level was 4.2 dBA greater than the average OBSI level in Year 1. By looking into the average change in sound intensity, a preliminary indication of differences in wearing rate could be developed, even considering the fact that there is a level of uncertainty in the measurement within each year and from year to year, primarily due to changes in test tire. The graphs in Figure 3.23, Figure 3.26, Figure 3.29, Figure 3.31, and Figure 3.33 show the year-to-year change in OBSI levels for all subsections of each texture type, with each figure showing one texture type. These results indicate that there is considerable year-to-year variability. However, assuming that the year-to-year variability is similar across all sections, changes with time in the OBSI on each section will become apparent as years of data are collected.

Once any initial "fins" or other fragile surface texture features from construction are knocked down, changes in OBSI on concrete pavement would be expected to change more slowly than on asphalt pavement because there is no raveling mechanism. It is uncertain after three years of data collection whether there is sufficient change in the texture of the concrete sections within the year-to-year variability, however preliminary assessment of trends was attempted. Figure 3.24, Figure 3.27, Figure 3.30, Figure 3.32, and Figure 3.34 show all three years of OBSI levels versus the age of the surface for each texture type, with all the texture condition categories included in each figure. Overall, newer diamond-ground and longitudinally tined sections exhibited the largest changes in their overall OBSI level over the three-year period.

Lack of sufficient data for the longitudinally broomed and diamond-grooved sections, and the age of the burlap drag sections, prevented any attempts to draw conclusions for those surface types.

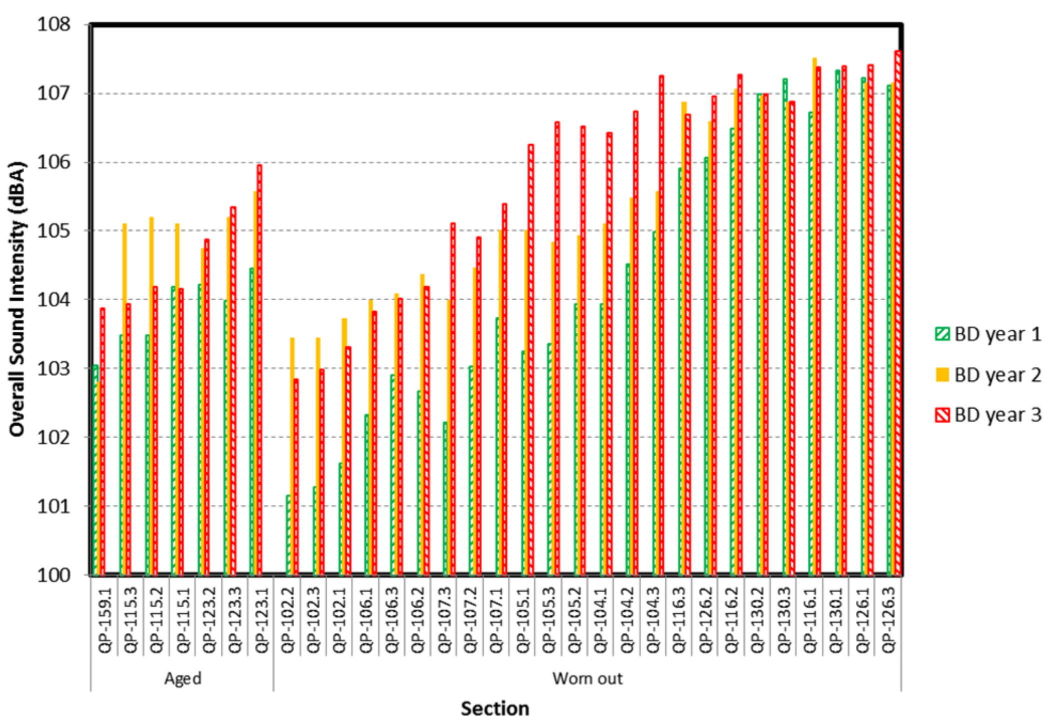


Figure 3.23: Burlap drag Year 1, 2 and 3 OBSI results for *aged* and *worn out* texture sections (no *new* condition sections measured).

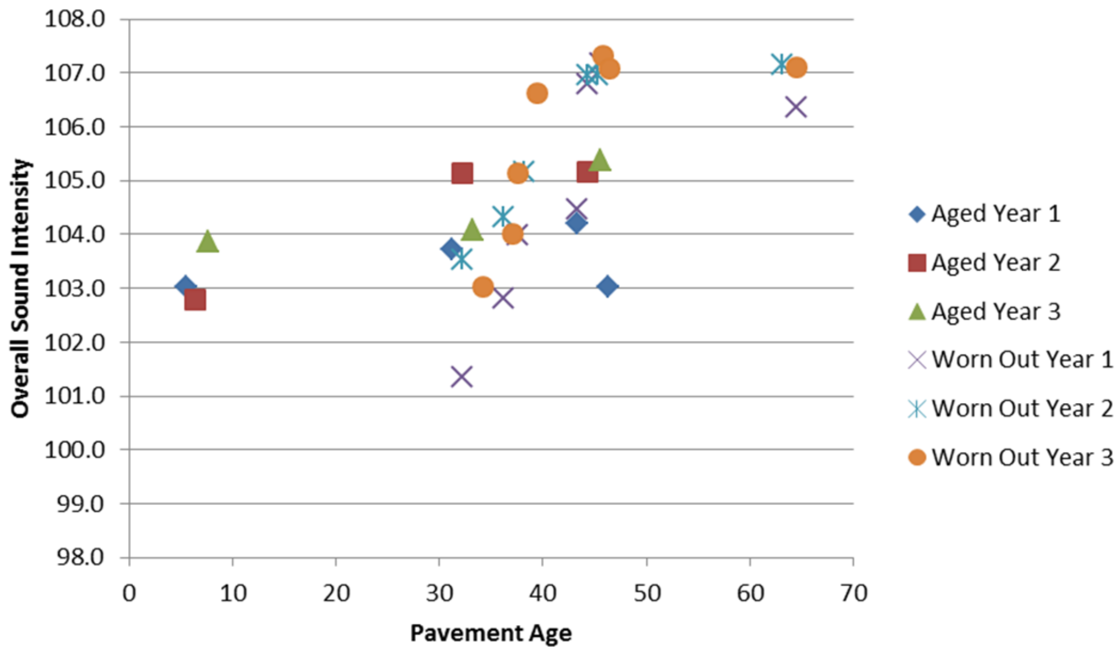


Figure 3.24: Burlap drag Year 1, 2 and 3 OBSI results versus years since last surfacing for *aged* and *worn out* texture sections (no *new* condition sections measured).

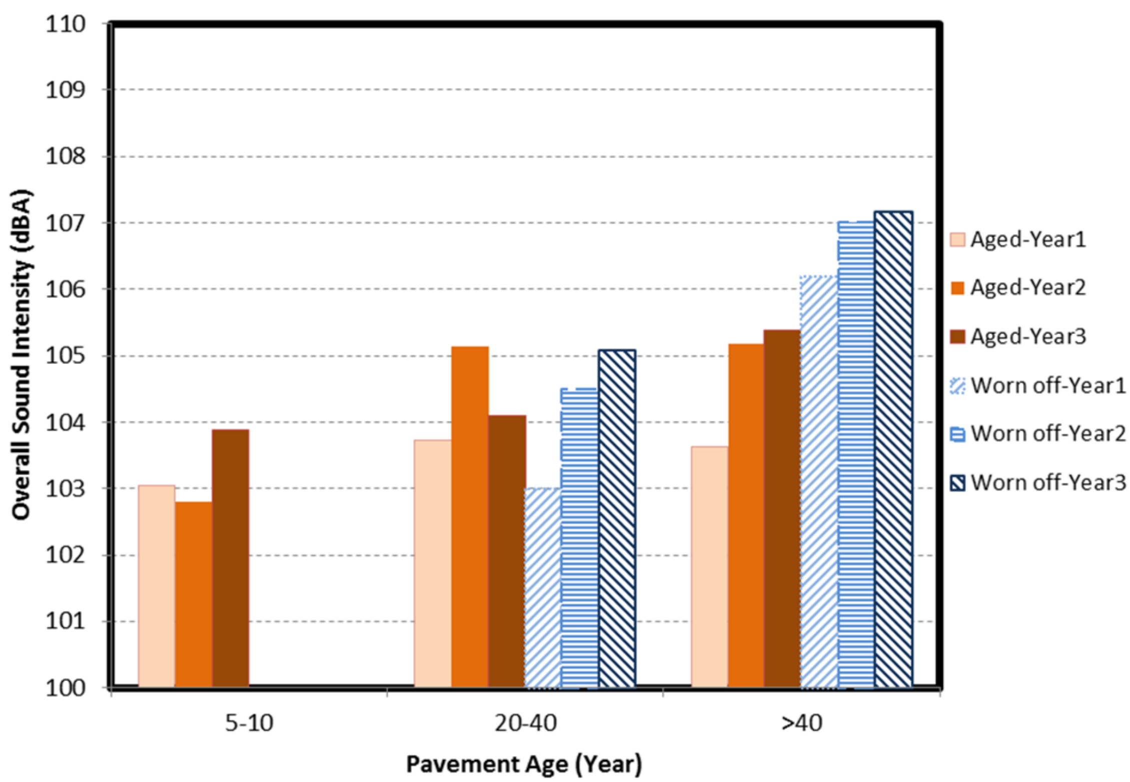


Figure 3.25: Average burlap drag Year 1, 2, and 3 OBSI results for *aged* and *worn out* texture sections (no *new* condition sections measured) by different age categories.

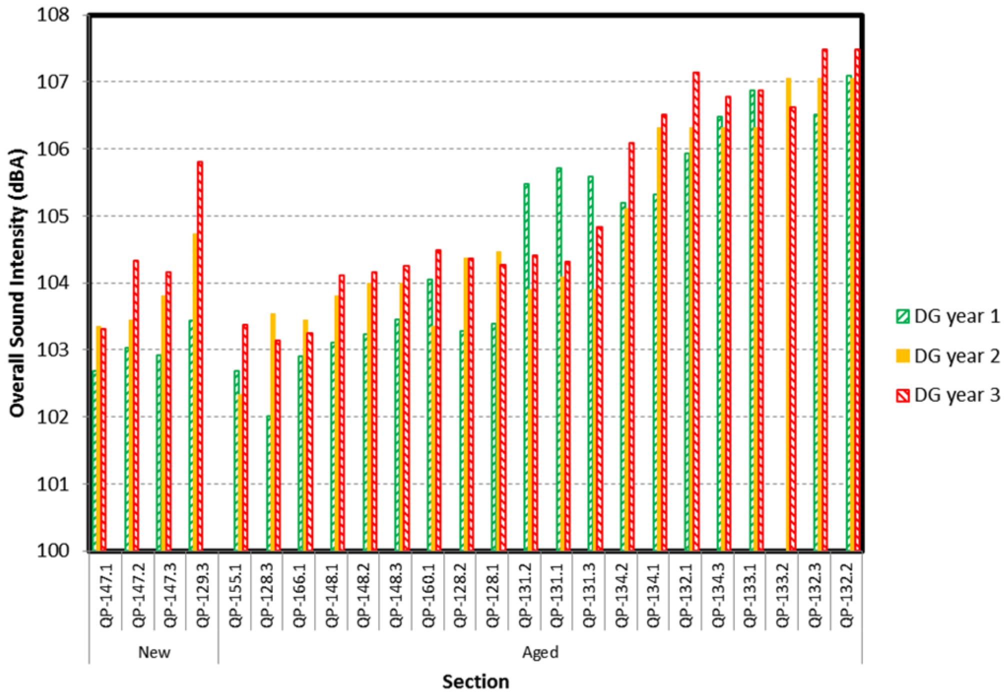


Figure 3.26: Diamond-ground Year 1, 2, and 3 OBSI results for *new* and *aged* texture sections (no *worn out* condition sections measured).

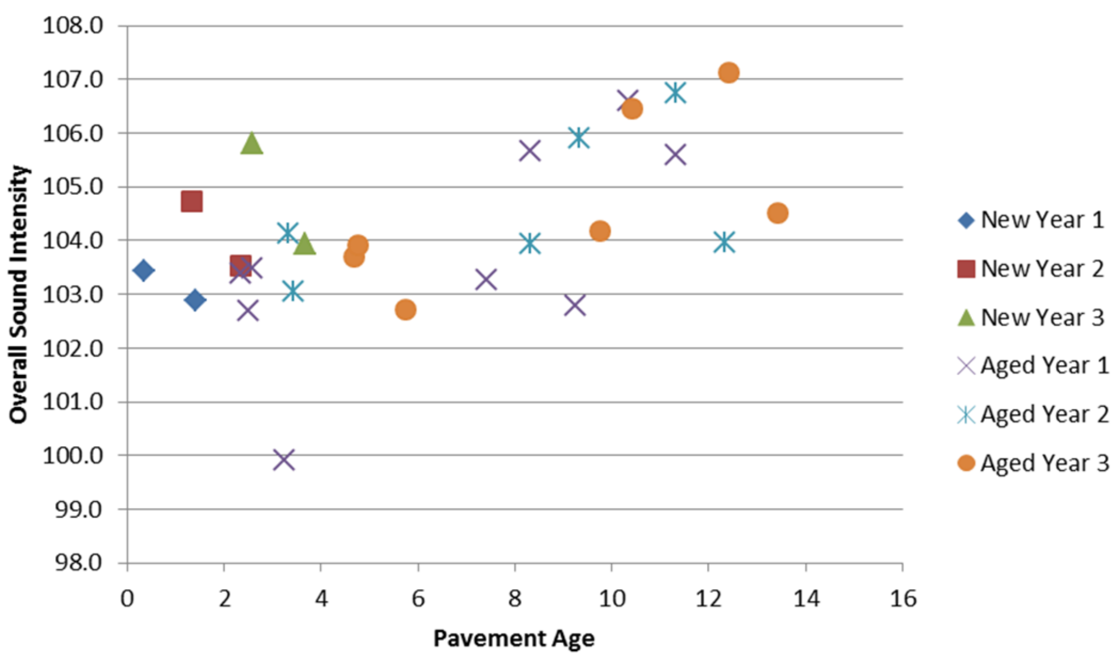


Figure 3.27: Diamond-ground Year 1, 2 and 3 OBSI results for *new* and *aged* texture sections (no *worn out* condition sections measured) versus years since last surfacing.

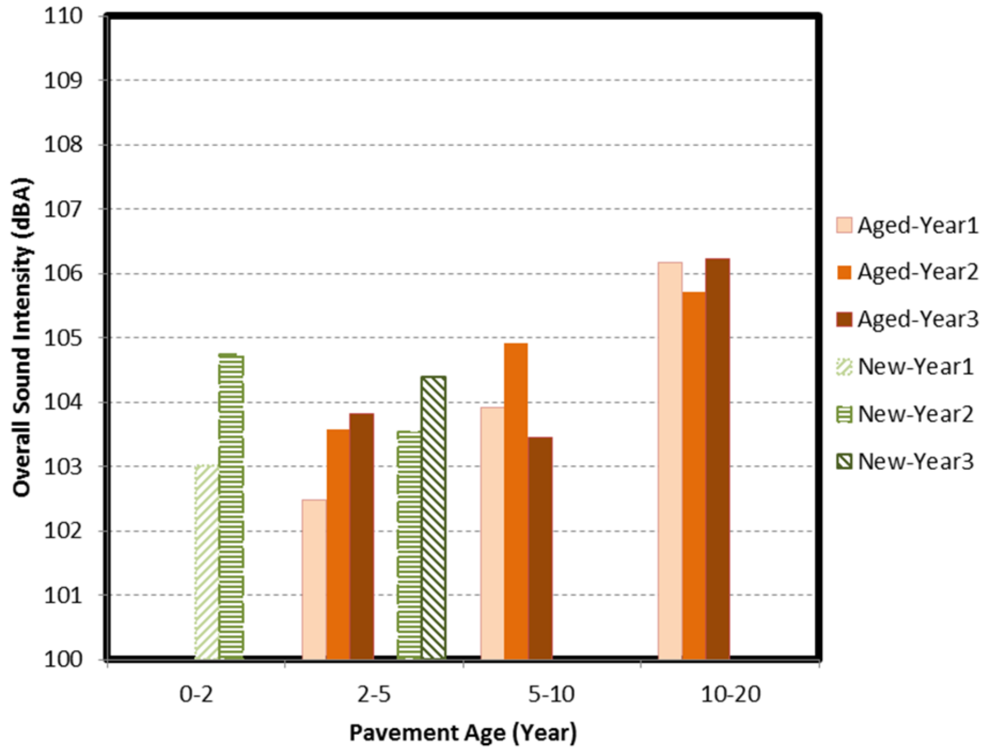


Figure 3.28: Diamond-ground Year 1, 2, and 3 OBSI results for *new* and *aged* texture sections (no *worn out* condition sections measured) for different age categories.

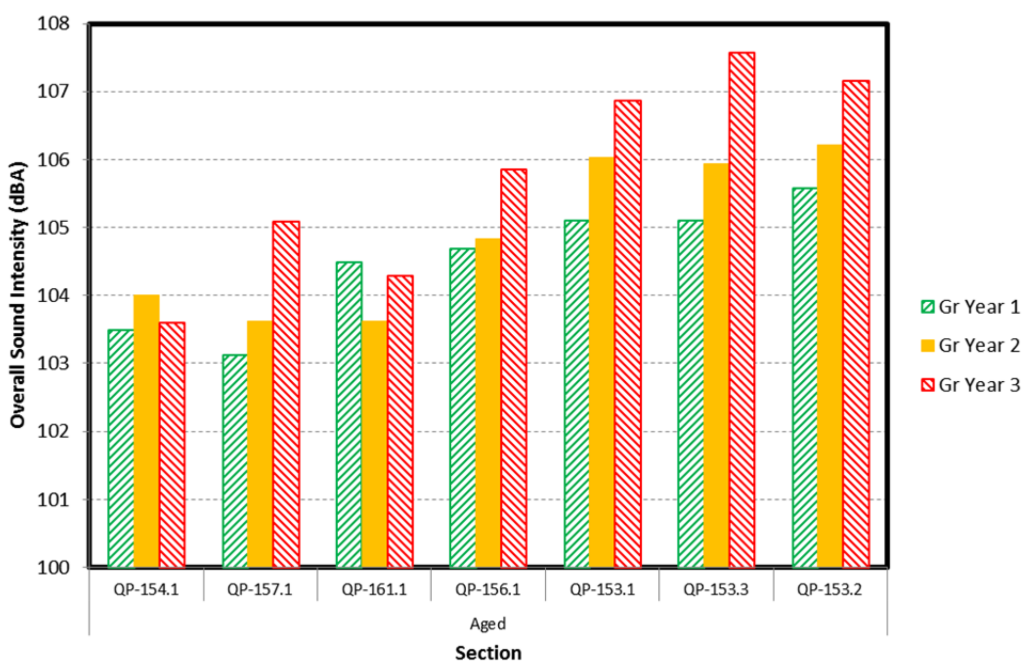


Figure 3.29: Diamond-grooved Year 1, 2, and 3 OBSI results for *aged* texture sections (no *new* or *worn out* condition sections measured).

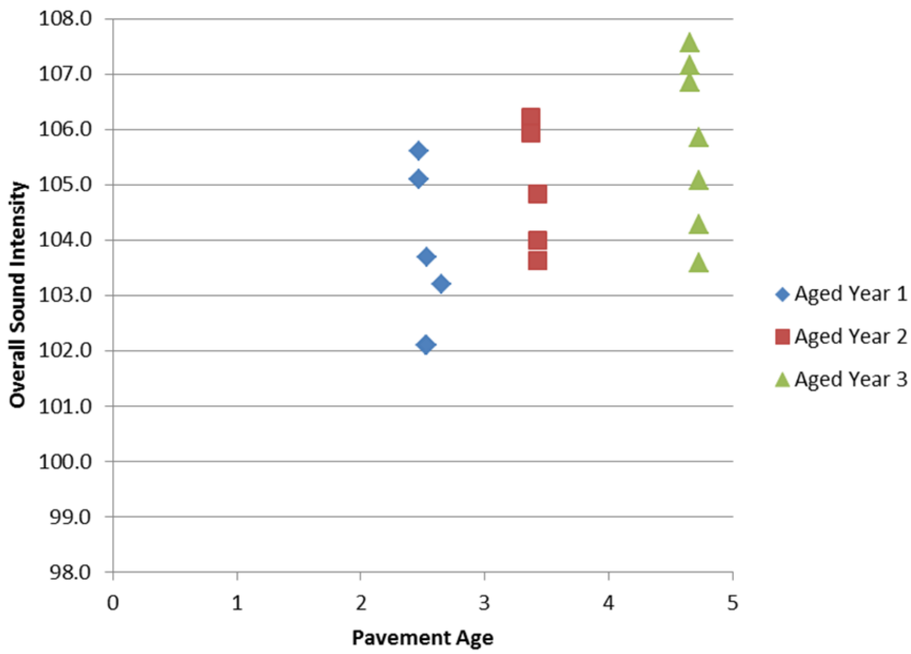


Figure 3.30: Diamond-grooved Year 1, 2, and 3 OBSI results for *aged* texture sections (no *new* or *worn out* condition sections measured) versus years since last surfacing.
(Note: the number of data points shown for each year in the figure varies because some subsections had identical values in some years.)

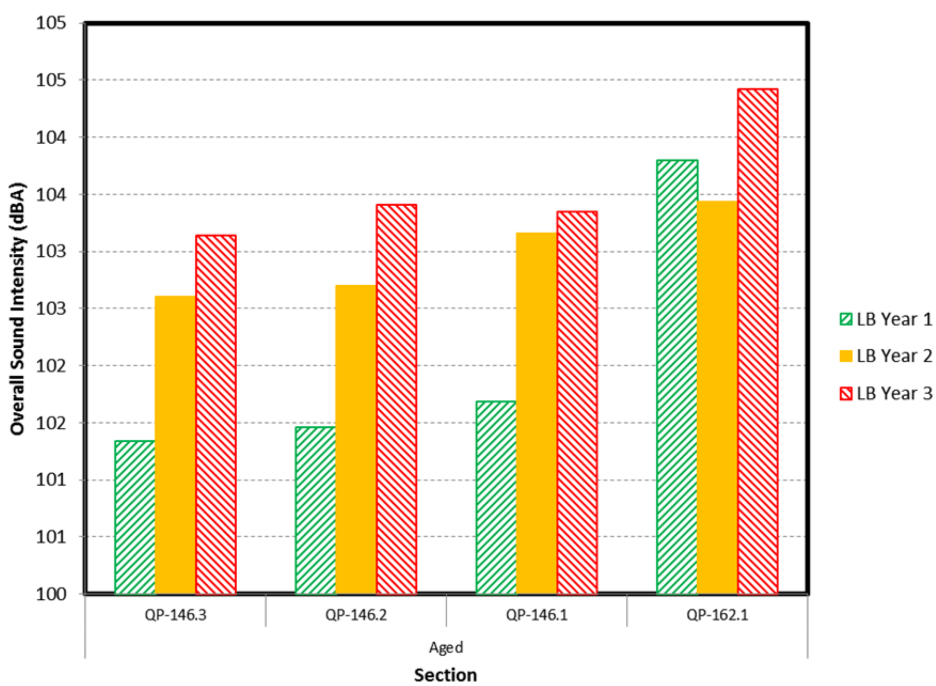


Figure 3.31: Longitudinally broomed Year 1, 2, and 3 OBSI results for *aged* texture sections (no *new* or *worn out* condition sections measured).

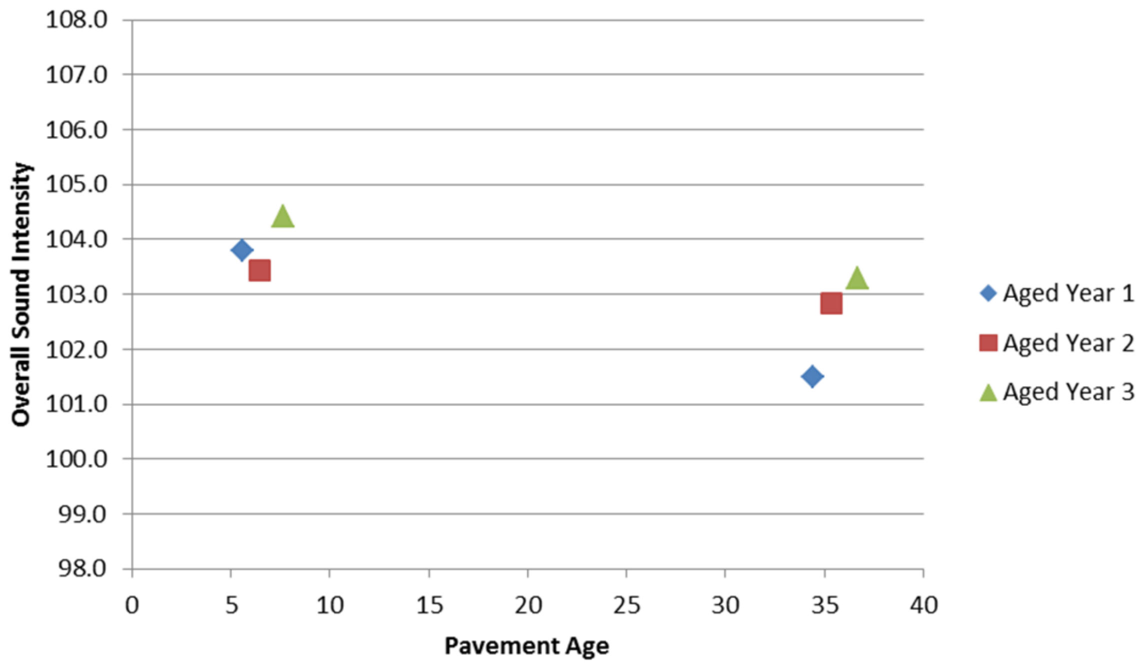


Figure 3.32: Longitudinally broomed Year 1, 2, and 3 OBSI results for *aged* texture sections (no *new* or *worn out* condition sections measured) versus years since last surfacing.

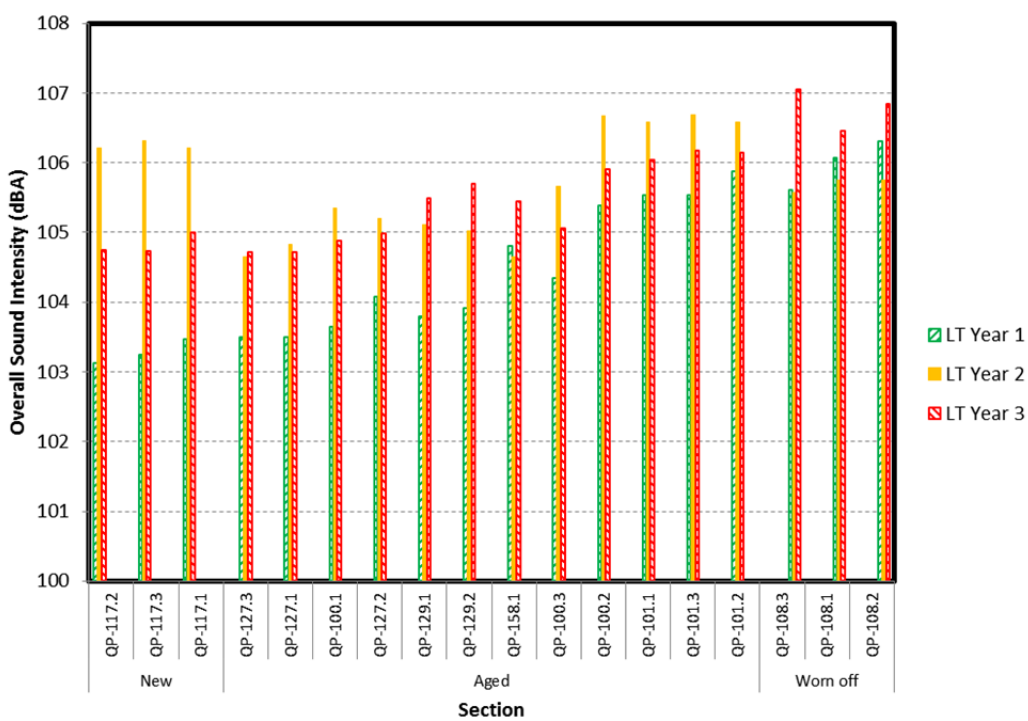


Figure 3.33: Longitudinally tined Year 1, 2, and 3 OBSI results for all texture conditions *(new, aged,* and *worn out).*

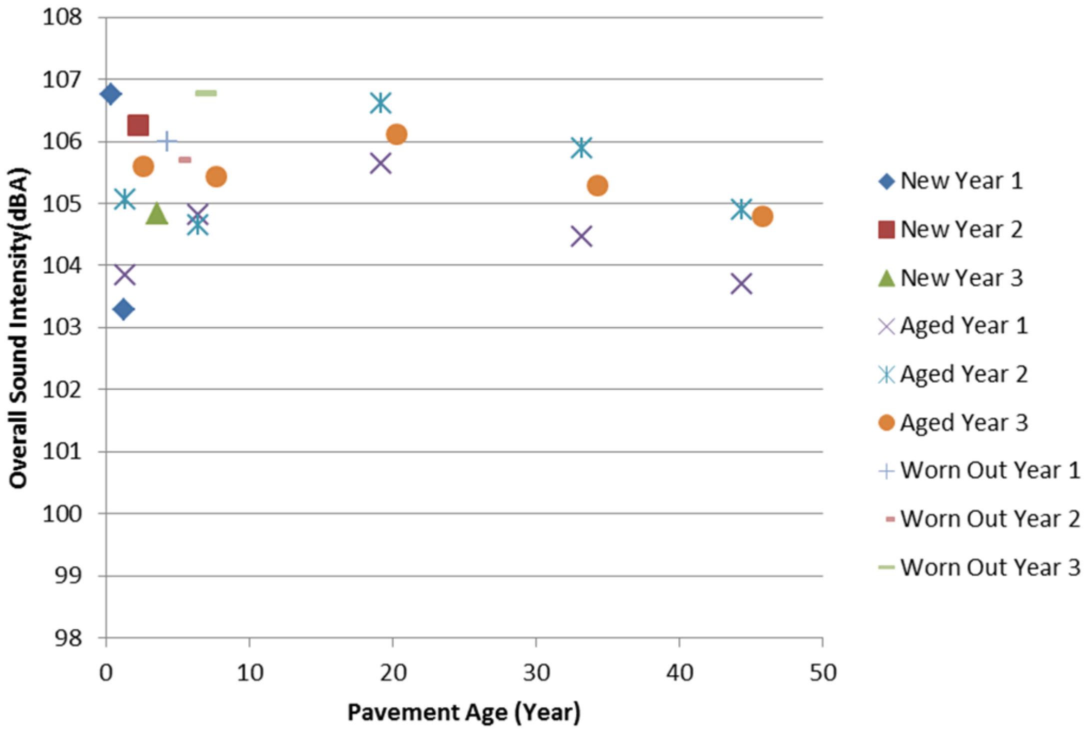


Figure 3.34: Longitudinally tined Year 1, 2, and 3 OBSI results for all texture conditions *(new, aged,* and *worn out)* versus years since last surfacing.

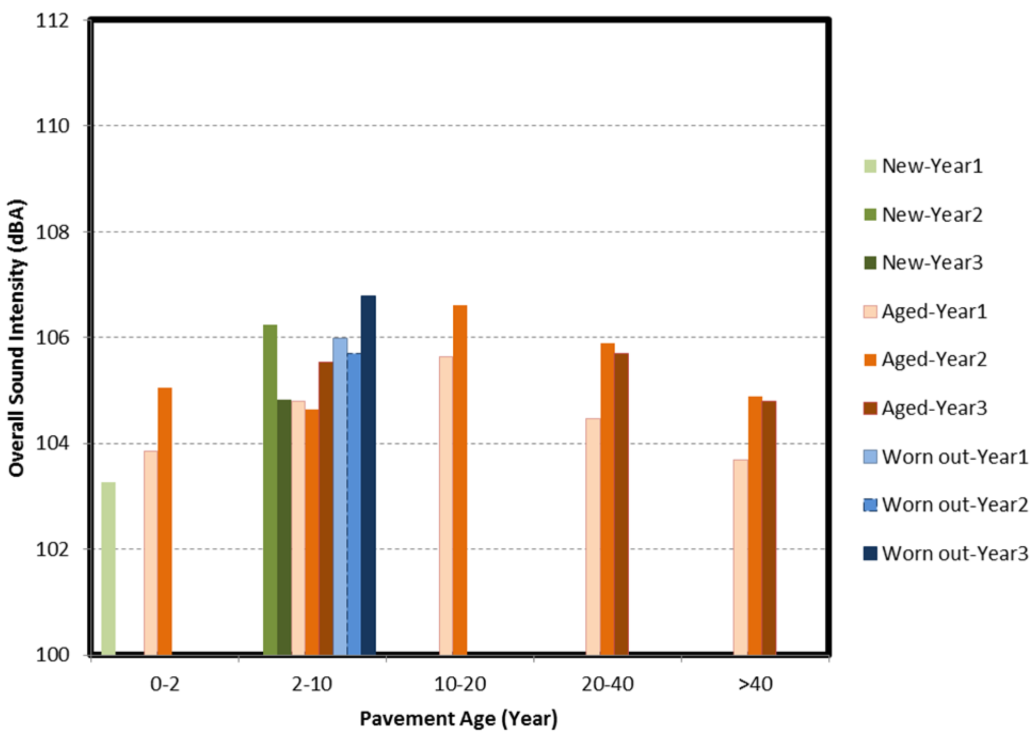


Figure 3.35: Longitudinally tined Year 1, 2, and 3 OBSI results for all texture conditions *(aged, worn out,* and *new)* for different age categories.

3.4 Effects of Joints on Tire/Pavement Noise

The measured OBSI levels presented in this report include the effects of joint slap, faulting, and sealant in addition to the effect of the pavement texture, each of which, 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 the joint below the surface acting as an amplifier for the sound of the tire passing over the joint. Faulting causes noise as the tire reacts to passing over the fault. Joint sealant that is present above the surface of the joint (referred to as *overbanded* sealant*)* creates positive texture which results in noise from tire vibration.

Faulting and overbanded sealant were not considered in the experiment described in this report and the previous two years of measurements because a method for measuring them using the high-speed profilometer had not been established, and photographs with sufficient detail to identify sealant overbanding were unavailable at the time the project scope was established. Measurement of joint opening cross-sectional area requires traffic closures. As described in Reference (*2*), some initial analysis was performed regarding the effects of joints on overall OBSI measurements, without separating the effects of slap caused by the joint groove, faulting, and overbanded sealant. That analysis, and more recent work by others, showed that joint effects can have an important effect on overall OBSI on a given section.

Some preliminary data indicating the added effects of joint faulting, joint opening cross-sectional area, and joint sealant recess depth on overall OBSI for concrete pavement surfaces has 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*).

Since the data collection and analysis for this report were completed, a method has been developed by Donavan 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 the joint below the surface of the pavement, which amplifies the sound of the tire passing across the joint, but it does not consider faulting or overbanded sealant (*8*). Based on these recent findings, the next year of concrete pavement noise measurements for this program, which will also be the final year for most sections, will include an effort to help separate the effects of texture and joint characteristics. This will be attempted by taking field measurements of joint faulting on a number of sections, and by measuring either unsealed joint depths and widths or overbanded sealant height. These results will also be used to help validate the model for joint opening cross-sectional area developed by Donavan, and to see whether the effects of joint faulting and sealant overbanding can be quantified.

It is expected that consideration of joint opening cross-sectional area, faulting and sealant overbanding will provide some explanation of variability within a given texture type. However, looking at the sections with *new* texture condition for the diamond-ground and longitudinally tined textures, which should not have any faulting or sealant overbanding, it can be seen that their OBSI levels are not that much different from those of sections with textures in the *aged* condition (Figure 3.18 and Figure 3.19), which fall in the range of approximately 103 to 107 dBA. This suggests that faulting and sealant overbanding may not be major contributors to the noise. It should be possible to better address this question when analyzing the next year of data by measuring fault height and checking for sealant overbanding using measurements (fault height) and photos (sealant overbanding), made possible by the new Automated Pavement Condition Survey (APCS), that have very recently become available.

4. ANALYSIS

4.1 Analysis of Results of this Study

Five different concrete texture types were evaluated in this study. These texture types represent ones that are either currently in use on concrete pavement projects in California or were used in the past: burlap drag, diamond ground, diamond grooved, longitudinally broomed, and longitudinally tined. However, the variability found visually 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 type. As a first attempt at characterizing these texture conditions in the previous report covering the first two years of measurements, each section was grouped into one of following the texture condition categories *new*, *aged* or *worn out* based on visual observation of texture wear. This chapter presents a detailed summary of the test results for each texture type and condition, and also compares the overall distribution of results for each texture type in this study to findings from a national study. In contrast with Chapter 3, which considered only data from sections for which data was collected in all three years of the study, the analysis for each texture type in Section 4.1 of this report includes all data collected across the three years, including data from sections for which only one or two years of data were collected. The comparison with the national study in Section 4.3 of this report only considers data from those sections for which three years of data were collected.

4.1.1 Burlap Drag

The oldest concrete pavement sections evaluated in this study have burlap drag texture, including sections on Interstate 80 in Solano County that have been in service for over 60 years (QP-116). Due to their long service life, some of the sections for this texture type have surfaces that show no signs of the initial surface texture, and were therefore categorized as *worn out* texture condition. Burlap drag sections are not constructed in California highways any more, which is why no "young" sections, other than the one built for the field evaluation experiment in Mojave (results shown in Section 4.2 of this report), were included in the experiment. This young section, which was about five years old when first tested, yielded an average OBSI level of about 102.7 dBA over three years of measurement. Other than this experimental section, however, all the burlap drag sections were older than 30 years and had OBSI levels ranging between 100.7 and 107.8 dBA in year-to-year measurements. These values indicate that the actions of traffic, often combined with rainfall, will tend to polish some concrete surfaces and to remove positive texture (stones protruding from the surface) without damaging the paste around the stones. The quieter sections appear to be those with shallow texture (based on observation of photos of the textures), as shown in Figure 4.1. Therefore, a possible reason for the variability of OBSI for the burlap drag sections is the variation in macrotexture caused by aggregates creating positive texture on the surface. Comparison of the photographed textures from the five-year old Mojave section and the quietest burlap drag section measured in this study (Figure 4.2) indicates that the slightly noisier Mojave section (QP-159) may have a smoother texture than the quieter QP-102.3, indicating that there is no visual evidence that the one should be quieter than the other.

A summary of the information for burlap drag sections is presented in Table 4.1.

Table 4.1: Summary Information for Burlap Drag Sections

Collection Year	Year 1	Year 2	Year 3
Number of sections evaluated	37 *(new:* 0, *aged:* 10, *worn out:* 27)	31 *(new:* 0, *aged:* 7, *worn out*: 24)	31 *(new:* 0, *aged:* 7, *worn out*: 24)
Average OBSI level (dBA)	104.2 (only *new* & *aged:* 103.6)	105.3 (only *new* & *aged:* 104.8)	105.6 (only *new* & *aged:* 104.6)
OBSI level interquartile range (dBA)	103.0 – 105.4 (only *new* & *aged:* 103.1 – 104.2)	104.4 – 106.9 (only *new* & *aged:* 104.8 – 105.2)	104.2 – 107.0 (only *new* & *aged:* 103.9 – 105.3)
OBSI level range (dBA)	101.2 – 107.3 (only *new* & *aged:* 102.6 – 104.4)	102.8 – 107.5 (only *new* & *aged:* 102.8 – 105.6)	102.8 – 107.6 (only *new* & *aged:* 103.9 – 105.9)
Range of surface age (years)	5.5 – 64.6		

QP-102.2 (102.5 dBA)

QP-107.3 (103.8 dBA)

QP-130.1 (107.3 dBA)

QP-116.1 (107.2 dBA)

Figure 4.1: Example photographs of burlap drag surfaces and their OBSI levels.

(a) QP-102.3 (102.3 dBA)

(b) Mojave burlap drag section (QP-159, 102.7 dBA)

Figure 4.2: Photographs of quietest aged burlap drag surfaces (QP-102.3 [102.3 dBA] and five-year old burlap drag section at Mojave.

4.1.2 Diamond Ground

A summary of the information for the diamond-ground surfaces is presented in Table 4.2. Highly variable texture depth (macrotexture) and the shape of the texture (sharp, rounded, wide versus narrow plateaus) is thought to be a likely reason for the variability in OBSI levels. Photographs of example diamond-ground surfaces are shown in Figure 4.3.

Without texture measurements and shape and depth characterization it is difficult to draw conclusions regarding which characteristics of the diamond-ground textures are causing high and low overall noise levels.

Table 4.2. Summary Information for Diamond-Ground Sections

Collection Year	Year 1	Year 2	Year 3
Number of sections evaluated	32 *(new:*4, *aged:* 29, *worn out*: 0)	24 *(new:* 4, *aged:* 20, *worn out*: 0)	27 *(new:* 4, *aged:* 23, *worn out*: 0)
Average OBSI level (dBA)	103.8 (only *new* & *aged:* 103.8)	104.7 (only *new* & *aged:* 104.7)	104.8 (only new & aged: 104.8)
OBSI level interquartile range (dBA)	102.8 – 105.4 (only new & *aged:* 102.8 – 105.4)	103.6 – 106.3 (only new & *aged:* 103.6 – 106.3)	103.4 – 106.5 (only *new* & *aged:* 103.4 – 106.5)
OBSI level range (dBA)	99.7 – 107.1 (only *new* & *aged:* 99.7 – 107.1)	102.3 – 107.1 (only *new* & *aged:* 102.3 – 107.1)	102.4 – 107.5 (only *new* & *aged:* 102.4 – 107.5)
Range of surface age (years)	0.3 – 13.4		

QP-155.1 (102.8 dBA)

QP-147.1 (103.1 dBA)

QP-134.1 (106.5 dBA)

QP-132.3 (107.0 dBA)

Figure 4.3: Example photographs of diamond-ground surfaces and their OBSI levels.

4.1.3 Diamond Grooved

The findings of this study for 19 diamond-grooved sections and 32 diamond-ground sections (7 and 24 sections in Year 2, and 7 and 27 sections in Year 3, respectively), indicate that the two techniques appear to yield similar OBSI levels. Comparison of Figure 3.27 (diamond ground) and Figure 3.30 (diamond grooved) shows that the experiment samples for both texture types consisted mainly of new surfaces, retextured after the originals were resurfaced. It can also be seen from Table 2.1 that the DG and Gr sample sections are distributed across both non-truck and truck lanes; and in both dry and wet parts of state except for the very wet North Coast region. A summary of the information for the diamond-grooved sections is presented in Table 4.3. Photographs of example diamond-grooved surfaces are shown in Figure 4.4. As with the diamond-ground sections, it is difficult without texture measurements and shape and depth characterization to attempt to draw conclusions regarding which characteristics of the diamond-ground textures are causing high and low overall noise levels.

Table 4.3. Summary Information for Diamond-Grooved Sections

Collection Year	Year 1	Year 2	Year 3
Number of sections evaluated	19 *(new:* 0, *aged:* 19, *worn out*: 0)	7 (new: 0, aged: 7, *worn out:* 0)	7 (new: 0, aged: 7, *worn out:* 0)
Average OBSI level (dBA)	104.3 (only *new* & *aged:* 104.3)	104.9 (only *new* & *aged:* 104.9)	105.8 (only *new* & *aged:* 105.8)
OBSI level interquartile range (dBA)	103.5 – 105.1 (only *new* & *aged:* 103.5 – 105.1)	103.6 – 106.0 (only *new* & *aged:* 103.6 – 106.0)	104.3 – 107.2 (only *new* & *aged:* 104.3 – 107.2)
OBSI level range (dBA)	102.1 – 105.6 (only *new* & *aged:* 102.1 – 105.6)	103.6 – 106.2 (only *new* & *aged:* 103.6 – 106.2)	103.6 – 107.6 (only *new* & *aged:* 103.6 – 107.6)
Range of surface age (years)	2.0 – 4.7		

QP-157.1 (103.9 dBA) **QP-161.1 (104.1 dBA)**

QP-156.1 (105.1 dBA) **QP-153.1 (106.0 dBA)**

Figure 4.4: Example photographs of diamond-grooved surfaces and their OBSI levels.

4.1.4 Longitudinally Broomed

As was noted in Section 3.2, the difference between the longitudinally broomed and burlap drag surface textures is only clear on surfaces that are not *worn out* and still show the striations caused by the texturing tool. This resulted in a low number of longitudinally broomed sections, which in turn unbalanced the experiment and made any interpretation of the results more complicated. It was also noted that from a practical point of view, longitudinal brooming can be considered equivalent to a "heavy drag" texture.

A summary of the information for longitudinally broomed sections is presented in Table 4.4. Photographs of examples of longitudinally broomed surfaces are shown in Figure 4.5.

The longitudinally broomed sections have a narrow range of overall OBSI values compared with the other textures, in large part due to the very small sample size. There is no readily apparent explanation for the differences between OBSI values for different sections based on the photographs of the texture conditions.

Table 4.4: Summary Table for Longitudinally Broomed Sections

Collection Year	Year 1	Year 2	Year 3
Number of sections evaluated	10 (*new:* 0, *aged:* 4, *worn out:* 6)	4 (*new:* 0, *aged:* 4, *worn out:* 0)	4 (*new:* 0, *aged:* 4, *worn out:* 0)
Average OBSI level (dBA)	103.7 (only *new* & *aged:* 102.1)	103.0 (only *new* & *aged:* 103.0)	103.6 (only *new* & *aged:* 103.6)
OBSI level interquartile range (dBA)	101.6 – 104.9 (only *new* & *aged:* 101.4 – 103.3)	102.6 – 103.4 (only *new* & *aged:* 102.6 – 103.4)	103.2 – 104.2 (only *new* & *aged:* 103.2 – 104.2)
OBSI level range (dBA)	101.3 – 106.4 (only *new* & *aged:* 101.3 – 103.8)	102.6 – 103.4 (only *new* & *aged:* 102.6 – 103.4)	103.1 – 104.4 (only *new* & *aged:* 103.1 – 104.4)
Range of surface age (years)	5.6 – 36.7		

QP-146.3 (102.4 dBA)

QP-146.2 (102.5 dBA)

QP-146.1 (102.7 dBA)

QP-162.1 (103.9 dBA)

Figure 4.5: Example photographs of longitudinally broomed surfaces and their OBSI levels.

4.1.5 Longitudinally Tined

A summary of the information for the longitudinally tined sections is presented in Table 4.5. The interquartile range reveals that the noise level of 50 percent of the sections of this texture type are expected to fall between 104.7 and 106.1 dBA. 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 shape (the grooves often appear to be "waves" of different wavelengths, but in other cases they are perfectly straight). This measured OBSI range therefore indicates that the different techniques used in longitudinally tining concrete pavement may result in pavements with similar noise characteristics. Four examples of longitudinally tined sections are shown in Figure 4.6. From the photographs it is interesting to note that Section QP-158.1, which has relatively smooth surfaces on the plateaus between the tine grooves and wide plateaus, and Section QP-100.2, which has narrower plateaus with rougher edges, have nearly the same OBSI value. Looking at the photograph of QP-127.3 (Figure 4.6, upper right), which is the quietest LT section when measurements over three years are averaged, does not provide a visual indication of why it should be quieter than the other LT sections.

Table 4.5: Summary Information for Longitudinally Tined Sections*

Collection Year	Year 1	Year 2	Year 3
Number of sections evaluated	21 (*new:* 6, *aged:* 12, *worn out:* 3)	21 (*new:* 6, *aged:* 12, *worn out:* 3)	21 (*new:* 6, *aged:* 12, *worn out:* 3)
Average OBSI level (dBA)	104.5 (only *new* & *aged:* 104.2)	105.1 (only *new* & *aged:* 106.7)	105.6 (only *new* & *aged:* 105.3)
OBSI level interquartile range (dBA)	103.5 – 105.6 (only *new* & *aged:* 103.5 – 105.4)	105.1 – 106.4 (only *new* & *aged:* 105.0 – 106.6)	104.9 – 106.1 (only *new* & *aged:* 104.8 – 105.9)
OBSI level range (dBA)	103.1 – 106.3 (only *new & aged:* 101.3 – 103.8)	104.6 – 106.7 (only *new & aged:* 102.6 – 103.4)	104.7 – 107.0 (only *new & aged:* 103.1 – 104.4)
Range of surface age (years)	0.3 – 45.8		

*QP-142 dropped from analysis due to excessive chain wear.

QP-158.1 (105.0 dBA)

QP-127.3 (104.3 dBA)

QP-101.1 (106.1 dBA)

QP-100.2 (106.0 dBA)

Figure 4.6: Example photographs of longitudinally tined surfaces and their OBSI levels.

4.2 Mojave Test Sections

Table 4.6 presents the results of the pavement sections in the Mojave test site (Kern 58). Figure 4.7 shows photographs of the surface textures on each of these sections. The Mojave sections—which are all of the same concrete mix and ages (with some textured in 2003 and others in 2006)—have been exposed to the same traffic and climate conditions. The quietest sections were those with a diamond-ground surface, and the loudest section had a longitudinally tined texture.

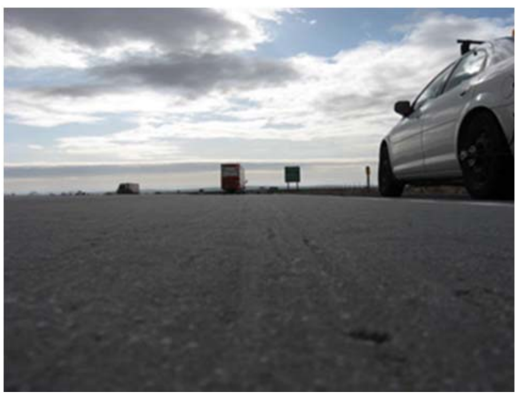
The results from the Mojave sections were compared to the range of noise levels measured for each texture type on the other sections from across the state, shown in Table 3.3. That comparison showed that the burlap drag, diamond-ground, diamond-grooved, and longitudinally tined textures at Mojave were generally quieter than the same textures on the rest of the state highway network, while the longitudinally broomed texture at Mojave was noisier than the few longitudinally broomed sections measured on the rest of the network.

The photos shown in Figure 4.7 indicate that QP-154, which showed a lower noise level compared to QP-156 and QP-157, has larger spacing between its grooves than either of those sections. For the diamond-ground sections, there is nothing apparent in the photos that distinguishes them from each other, and they have similar noise levels.

Table 4.6: Summary Information for Mojave Sections

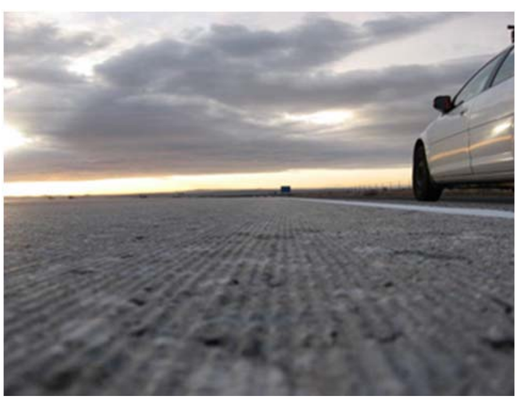
Section ID	Location	Texture	Construction Year	Surfacing Year	OBSI Level Year 1 (measured Jan 2009)	OBSI Level Year 2 (measured Dec 2009)	OBSI Level Year 3 (measured Mar 2011)
QP-159.1	06Ker58E110.3	BD	2003	2003	101.9	102.2	103.9
QP-155.1	06Ker58E110.6	DG	2003	2006	101.2	101.7	103.4
QP-160.1	06Ker58E110.0	DG	2003	2006	102.7	102.9	104.5
QP-166.1	06Ker58E111.7	DG	2003	2006	101.7	103.0	103.3
QP-154.1	06Ker58E110.2	Gr	2003	2006	102.1	103.7	103.6
QP-156.1	06Ker58E111.2	Gr	2003	2006	103.7	104.7	105.9
QP-157.1	06Ker58E111.4	Gr	2003	2006	102.1	103.2	105.1
QP-161.1	06Ker58E110.4	Gr	2003	2006	103.2	103.2	104.3
QP-162.1	06Ker58E111.5	LB	2003	2003	102.5	103.0	104.4
QP-158.1	06Ker58E109.5	LT	2003	2003	103.6	104.4	105.4

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.

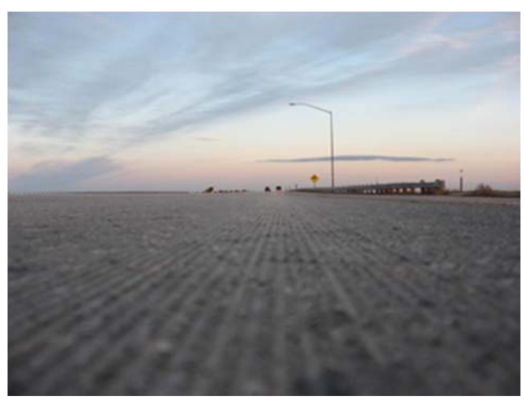


QP-159 (BD, $Y_{1,2,3}$ = 101.9, 102.2, 103.9 dBA)

QP-155 (DG, $Y_{1,2,3}$ = 101.2, 101.7, 103.4 dBA)



QP-160 (DG, $Y_{1,2,3}$ = 102.7, 102.9, 104.5 dBA)



QP-166 (DG, $Y_{1,2,3}$ = 101.7, 103.0, 103.3 dBA)

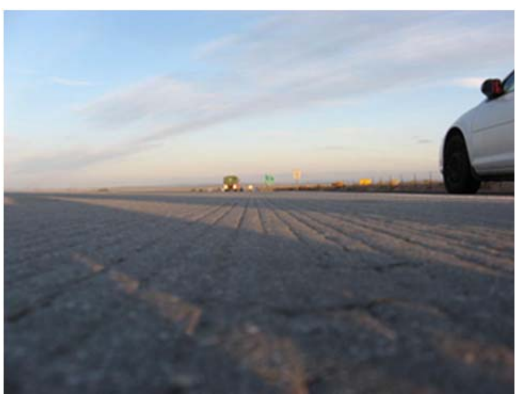
Example photographs of surface textures and their OBSI levels for the Mojave test sections
(continued on next page)

QP-154 (Gr, $Y_{1,2,3}$ = 102.1, 103.7, 103.6 dBA)

QP-156 (Gr, $Y_{1,2,3}$=103.7, 104.7, 105.9 dBA)

QP-157 (Gr, $Y_{1,2,3}$ = 102.1, 103.2, 105.1 dBA)

QP-162 (LB, $Y_{1,2,3}$ = 102.5, 103.0, 104.4 dBA)



QP-158 (LT, $Y_{1,2,3}$ = 103.6, 104.4, 105.4 dBA)

Figure 4.7: Example photographs of surface textures and their OBSI levels for the Mojave test sections.

4.3 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, as shown in Figure 4.8.

The study presented in this report included diamond-grooved and longitudinally broomed texture types but did not include transverse tining, which has only been used on bridge decks and not on pavements on California state highways (Figure 4.9). Table 4.7 compares the rankings for the common texture types that are included in both reports. There is agreement between the 2008 NCPTC report and this study in that both found diamond-ground surfaces to be quieter than most surfaces; that longitudinally tined surfaces are generally noisier than diamond-ground surfaces; and, that tire/pavement noise levels on burlap drag sections were between those of diamond-ground and longitudinally tined surfaces.

Although the rankings are similar, the OBSI levels included in the 2008 NCPTC report were consistently lower than those measured in this study. The reason for this was later identified through back-to-back measurements in a "rodeo" comparison of OBSI measurements on the same sections and was attributed to differences in the noise-collecting equipment and the type of test tire. Direct comparison of the measured values could not be made between the 2008 NCPTC study and the results from this study, primarily due to the differences in tires. Later, the equipment used in the national study was modified and the tires were standardized. This enabled a comparison of the trends and relative rankings between different textures types to be made, as shown in Figure 4.8 and Figure 4.9.

A more recent conference presentation, titled "Quieter Concrete Pavements: An Update of Pooled Fund TPF-5(139)" in October 2010 at the Pavement Evaluation Conference in Roanoke, Virginia, indicates that the NCPTC data is indicating higher OBSI levels than those shown previously. Continued comparisons of California data and NCPTC data will be worthwhile to identify common conclusions and where California and NCPTC data differ. In addition, comparison will provide better understanding of reasons for variability within surface textures.

Table 4.7: Ranked Order of Quieter Textures from Three Years of Measurements in this Study and the 2008 NCPTC Report (from Quietest to Noisiest)

Ranking in This Study based on all sections (*New, Aged*)	Ranking in This Study based on all sections (*New, Aged, Worn Out*)	Ranking in the 2008 NCPTC Report*
1. Longitudinally broomed (Avg. 102.5 dBA)	1. Longitudinally broomed (Avg. 102.5 dBA)	1. Diamond ground
2. Burlap drag (Avg. 104.3 dBA)	2. Avg. Diamond ground (Avg. 104.4 dBA)	2. Burlap drag
3. Diamond ground (Avg. 104.4 dBA)	3. Diamond grooved (Avg. 104.8 dBA)	3. Longitudinally tined
4. Diamond grooved (Avg. 104.8 dBA)	4. Burlap drag (Avg. 104.9 dBA)	4. Transversely tined
5. Longitudinally tined (Avg. 104.9 dBA)	5. Longitudinally tined (Avg. 105 dBA)	

* A different tire type was used than in the UCPRC study.

Another NCPTC noise study from 2006 that compared U.S. and European concrete pavement noise reduction methods (*10*) established somewhat arbitrary categories for interpretation of findings, as follows:

Zone 1: Low noise level or "Innovation Zone" (up to 99/100 dBA)

Zone 2: Mid noise level or "Quality Zone" (99/100 dBA to 104/105 dBA)

Zone 3: High noise level or "Avoid Zone" (104/105 dBA and above)

Table 4.8 and Table 4.9 show the data collected over the three years of this study summarized by the condition category definitions for the *new* and *aged* texture categories. Table 4.8 shows data for the sections collected in the third year and Table 4.9 shows the measurements taken during the entire three years of this study. It can be seen that none of the sections tested had noise levels less than 99 dBA, and that the noise levels for DG and LT, which have the largest sample sizes, are distributed across Zones 2 and 3 as defined by the NCPTC report.

Table 4.8: Summary of Measurements from Third Year of Measurements in This Study by Noise Level Categories from 2006 NCPTC Report

Texture Type	Sound Intensity <99 dBA	Sound Intensity ≥99 and <105 dBA	Sound Intensity ≥105 dBA	Sample Size
BD	0	71%	29%	7
DG	0	65%	35%	23
Gr	0	29%	71%	7
LB	0	100%	0%	4
LT	0	40%	60%	15
Total	0	57%	43%	56

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.

Table 4.9: Summary of Measurements from All Three Years of Measurements in This Study by Noise Level Categories from 2006 NCPTC Report

Texture Type	Sound Intensity <99 dBA	Sound Intensity ≥99 and <105 dBA	Sound Intensity ≥105 dBA	Sample Size
BD	0	67%	33%	21
DG	0	67%	33%	69
Gr	0	48%	52%	21
LB	0	100%	0%	12
LT	0	47%	53%	45
Total	0	61%	39%	168

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.

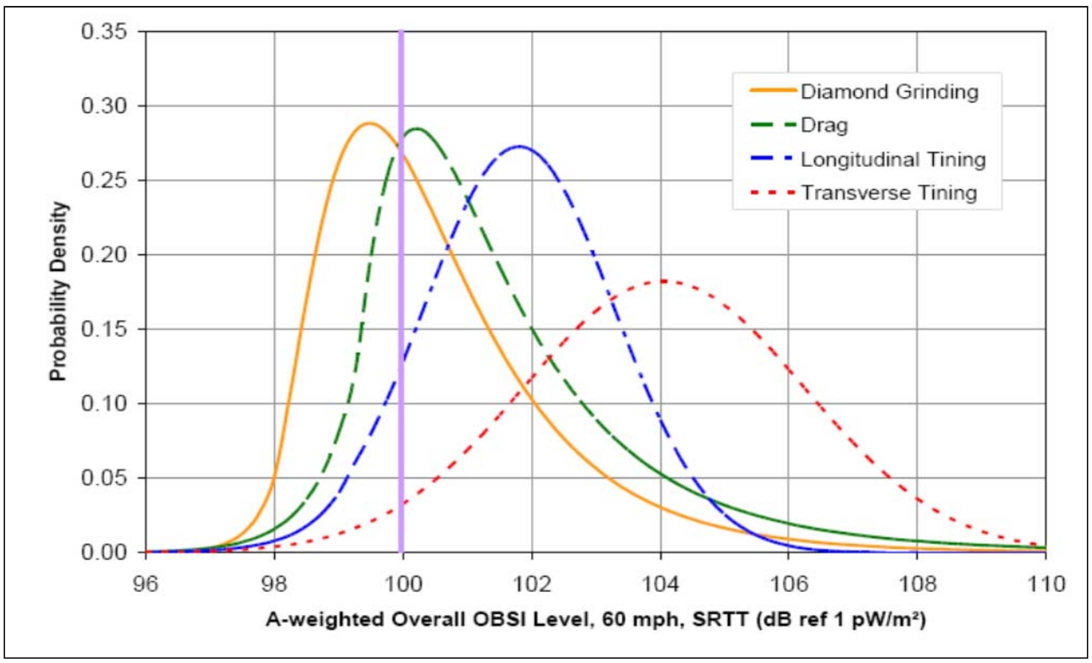


Figure 4.8: Probability distributions of OBSI noise levels for concrete pavement textures as reported by the National Concrete Pavement Technology Center (*9*).

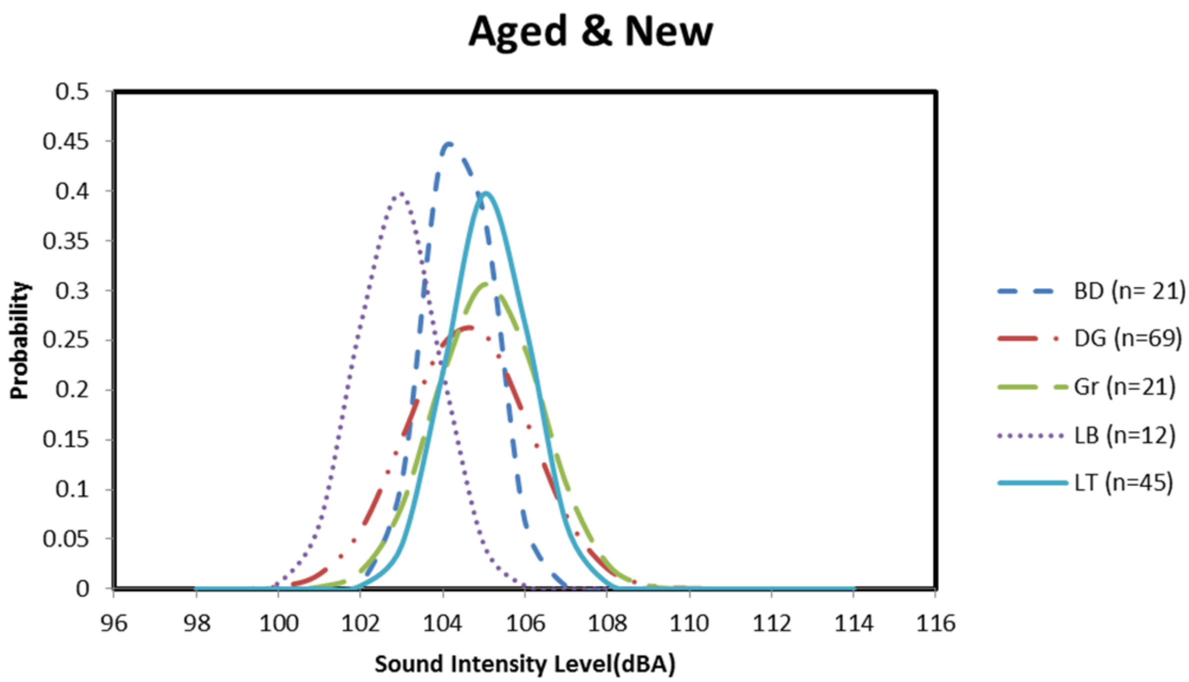


Figure 4.9: Distributions of OBSI noise levels in this study for all sections with *new* and *aged* textures.
(Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.)

Another research study was conducted by the National Cooperation Highway Research Program (NCHRP) in 2009 *(11)*. The NCHRP study measured 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. Table 4.10 shows the mean sound intensities for the texture types that were considered to be the same as those used in California measured across all of the states with an Aquatred tire, which is different from the SRTT tire used in the UCPRC study.

It can be seen that except for the longitudinally broomed sections, the measured noise levels in the NCHRP and this research study are very close, within 0.3 to 0.7 dBA, even though the test tires are different. Table 4.11 shows the data collected in California during the NCHRP study, which are from the same Mojave sections tested by the UCPRC.

Table 4.10: Sound Intensities for Different Texture Types in this Study Averaged for All *New*, *Aged,* and *Worn Out* Sections Compared to NCHRP Study

Texture Type	Sound Intensity in NCHRP Study	Sound Intensity in This Study
1. Longitudinally broomed	105.5	102.5
2. Diamond ground	105.1	104.4
3. Diamond grooved	105.2	104.8
4. Burlap drag	104.5	104.9
5. Longitudinally tined	105.3	105.0

Table 4.11: Sound Intensities for Different Texture Types in California Measured in NCHRP Study

Section ID	Highway	Direction	Construction Year	Measurement Date	Texture	Sound Intensity (dBA)
1045	58	EB	2003	11/11/2005	BD	104.5
1002	58	EB	2003	11/11/2005	DG	105.6
1005	58	EB	2003	11/11/2005	DG	104.5
1003	58	EB	2003	11/11/2005	Gr	104.8
1004	58	EB	2003	11/11/2005	Gr	105.3
1007	58	EB	2003	11/11/2005	Gr	105.6

Near-Field Noise (GM standard), as measured with proprietary single-probe receptor and noise equipment, and Goodyear Aquatred III test tire, mounted on an all-wheel drive Honda CR-V test vehicle.

Note: BD = burlap drag, DG = diamond ground, Gr = diamond grooved, LB = longitudinally broomed, LT = longitudinally tined.

5. CONCLUSIONS AND RECOMMENDATIONS

The primary purpose of this study was to evaluate the acoustic performance of concrete pavement surfaces in several experimental test sections and to quantify the impact of texture type and texture condition *(new, aged,* and *worn out)* on On-board Sound Intensity (OBSI) levels. To date this study has characterized the acoustic performance of concrete pavement surface texture types and quantified the impacts of texture type and condition on OBSI levels, with results obtained from OBSI measurements of tire/pavement interaction showing the following:

1. At this time no single concrete pavement texture type can be considered definitively quieter than the others. Each pavement type has a demonstrated range of noise levels that largely overlap.
2. The difference between the lowest and highest OBSI levels for the same nominal texture type is up to 6 dBA, indicating a large variability within a given texture type when sampled over a wide range of ages. The contributions of joint width, faulting, and sealant overbanding to this variance have not been rigorously investigated, and the results to date include these effects, which are part of the total noise generated by concrete pavements in the state.
3. Taking into account all sections, the OBSI level on existing concrete pavements in California varies from about 101.1 dBA to about 107.6 dBA.
4. If 105 dBA (based on the criterion separating the "Quality Zone" and the "Avoid Zone" from the 2006 NCPTC study) is selected as the upper threshold level that distinguishes between pavements with acceptable and unacceptable noise levels (*9*), about 52 percent of the burlap drag sections, 67 percent of the diamond-ground sections, 48 percent of the diamond-grooved sections, 100 percent of the longitudinally broomed sections, and 44 percent of the longitudinally tined sections tested for this study fall in the acceptable range.
5. The ranking of texture types for the sections with *new* and *aged* textures evaluated in this research project from quietest to loudest, is shown below.
   - Longitudinally broomed (n = 4, 102.5, *101.1 to 104.4)*
   - Burlap drag (n = 31, 104.3, *102.8 to 105.9)*
   - Diamond ground (n = 24, 104.4, *101.2 to 107.5)*
   - Diamond grooved (n = 7, 104.8, *102.1 to 107.6)*
   - Longitudinal tined (n = 18, 105.0, *102.7 to 106.8)*

   The first number following the texture type indicates the sample size, the second number indicates the average overall OBSI excluding the *worn out* texture condition averaged over three years of measurements, and the range of numbers in italic indicates the minimum and maximum values of overall OBSI excluding sections with *worn out* texture.
6. If a quieter pavement with an OBSI level less than 105 dBA (based on the NCPTC criterion) is needed, the data collected to date indicate that each of the textures evaluated can be used, however the characteristics of those textures that produce lower noise levels have not been clearly identified.

7. From these data, it is possible to identify a few sites that should be of interest for a more detailed investigation. These include the diamond-ground concrete pavement on US-50 (Yolo County), which is among the quietest pavements in this study and appears stable in terms of its acoustical durability, and the Mojave Desert sections, which have the same concrete mix design and experience the same traffic and environmental conditions.

In preparing for a fourth and final year of data collection and analysis on a large set of concrete pavement noise test sections, several observations are clear. First, the texture condition categorized by visual observation (*new, aged, worn out*) has not offered sufficient information to explain the reasons for variation in noise level within each texture type. It appears that a more in-depth characterization of the pavement textures—besides their nominal type and condition—is necessary to explain differences within texture type. Second, burlap drag does not appear to be a viable surface texture due to noise levels, although long-term data from the Mojave sections may later revive interest in this texture, as well as the longitudinally broomed texture. Third, the effects of joint width, faulting, and sealant overbanding on measured OBSI levels need to be considered.

Based on these observations and the conclusions to date, the following recommendations are made for the fourth and final year of large-scale data collection and analysis on concrete pavement noise:

1. Only include concrete pavements with diamond-grooving, diamond-grinding, and longitudinally tined surface textures, as well as the experimental New Generation Concrete Surface (NGCS) sections combining diamond-grinding and grooving so that the factors that contribute to the wide range of OBSI values for these most promising texture types can be better understood.
2. Expand the experiment for these texture types to include more sites, and be better balanced to create a factorial design with regard to age, traffic, and geographical location.
3. Consider faulting and sealant overbanding in the analysis of future data, and—using traffic closures—perform more detailed surface characterization on a subset of sections in the experiment; include measurement of joint widths and performance of texture scans in this characterization. These texture measurements can be used to see if characteristics of the joints and texture details help explain differences within each texture type for overall noise levels and frequency by frequency noise levels.
4. Test only one section at each site (the number of sections at each site is currently either one, two, or three) in order to simplify the field measurement, statistical analyses, and communication of the results. The reduction in the number of sections at each site will be offset by the increased number of sites which should produce a more widespread sample of each type of texture across the state. The data collected to date with multiple subsections has provided sufficient data needed to understand variability within sites.

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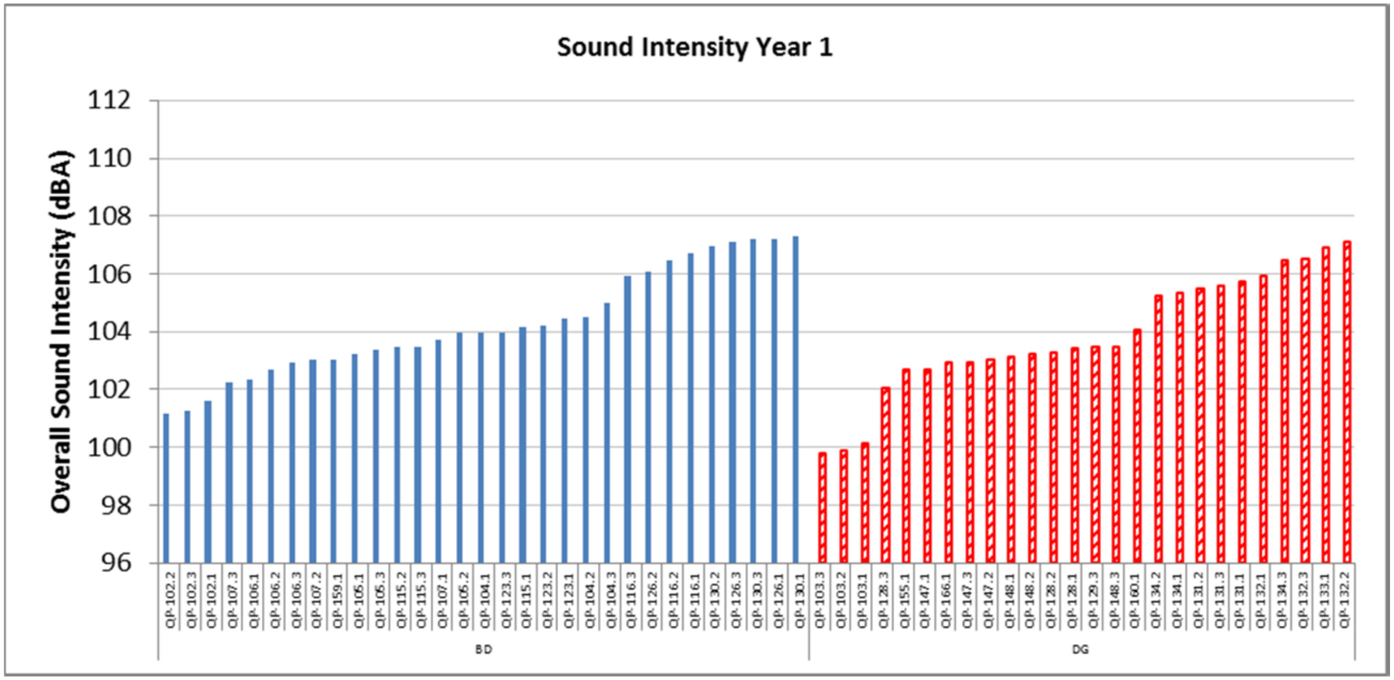
APPENDIX A: OBSI BAR CHARTS

The overall OBSI levels of each section measured in Year 1 and Year 2 are presented here.



Sound Intensity Year 1
Overall Sound Intensity (dBA)
112
110
108
106
104
102
100
98
96
QP-102.2
QP-102.3
QP-102.1
QP-107.3
QP-106.1
QP-106.2
QP-106.3
QP-107.2
QP-159.1
QP-105.1
QP-105.3
QP-115.2
QP-115.3
QP-107.1
QP-105.2
QP-104.1
QP-123.3
QP-115.1
QP-123.2
QP-123.1
QP-104.2
QP-104.3
QP-116.3
QP-126.2
QP-116.2
QP-116.1
QP-130.2
QP-126.3
QP-130.3
QP-126.1
QP-130.1
QP-103.3
QP-103.2
QP-103.1
QP-128.3
QP-155.1
QP-147.1
QP-166.1
QP-147.3
QP-147.2
QP-148.1
QP-148.2
QP-128.2
QP-128.1
QP-129.3
QP-148.3
QP-160.1
QP-134.2
QP-134.1
QP-131.2
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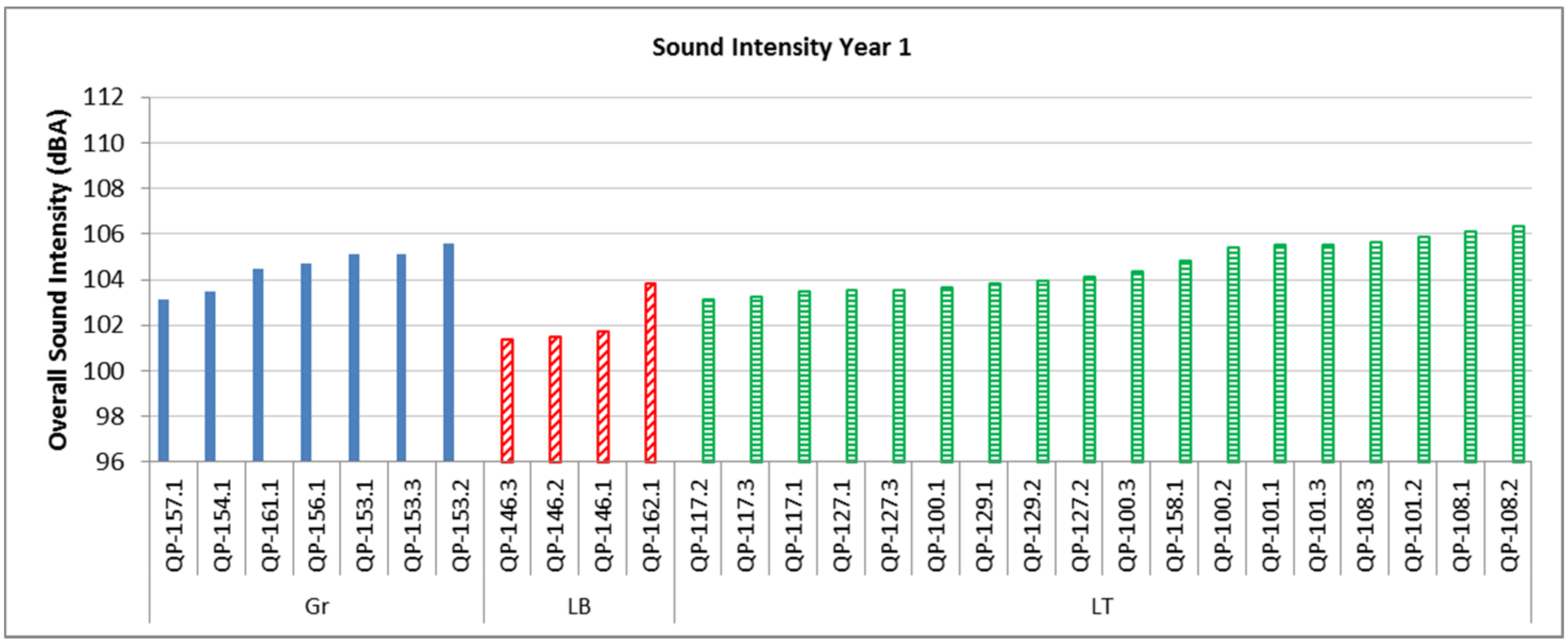
QP-134.3
QP-132.3
QP-133.1
QP-132.2
BD
DG



Sound Intensity Year 1
Overall Sound Intensity (dBA)
112
110
108
106
104
102
100
98
96
QP-157.1
QP-154.1
QP-161.1
QP-156.1
QP-153.1
QP-153.3
QP-153.2
QP-146.3
QP-146.2
QP-146.1
QP-162.1
QP-117.2
QP-117.3
QP-117.1
QP-127.1
QP-127.3
QP-100.1
QP-129.1
QP-129.2
QP-127.2
QP-100.3
QP-158.1
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QP-108.2
Gr
LB
LT

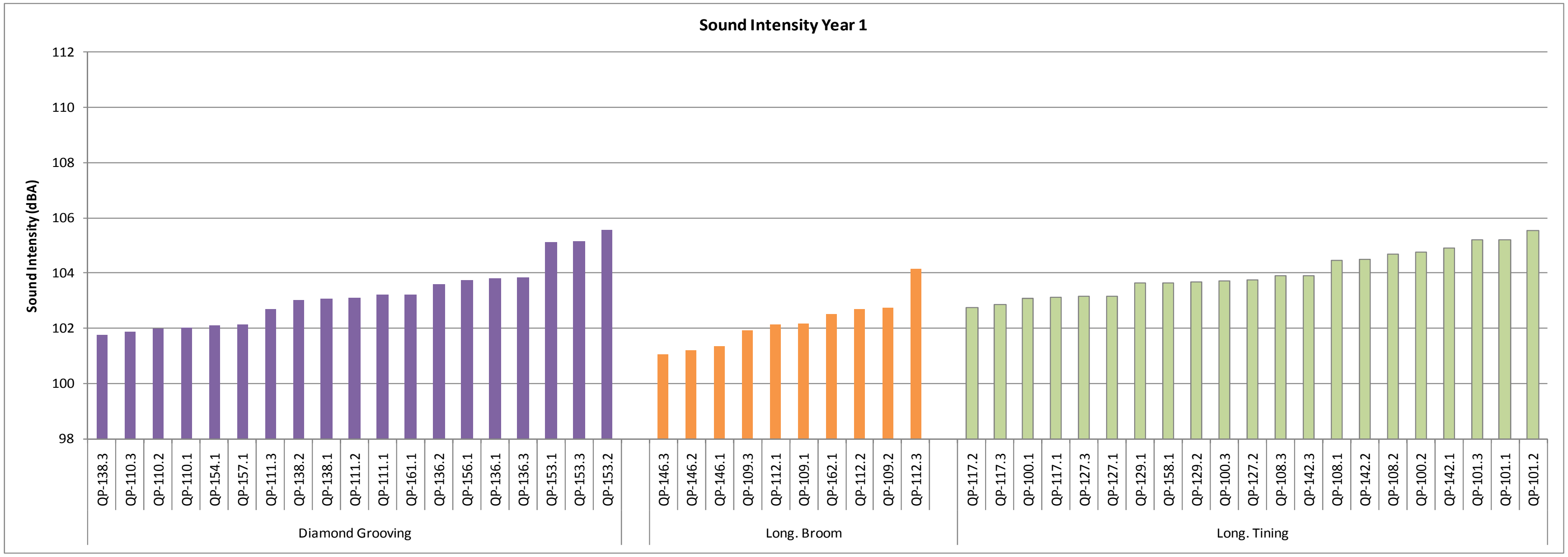
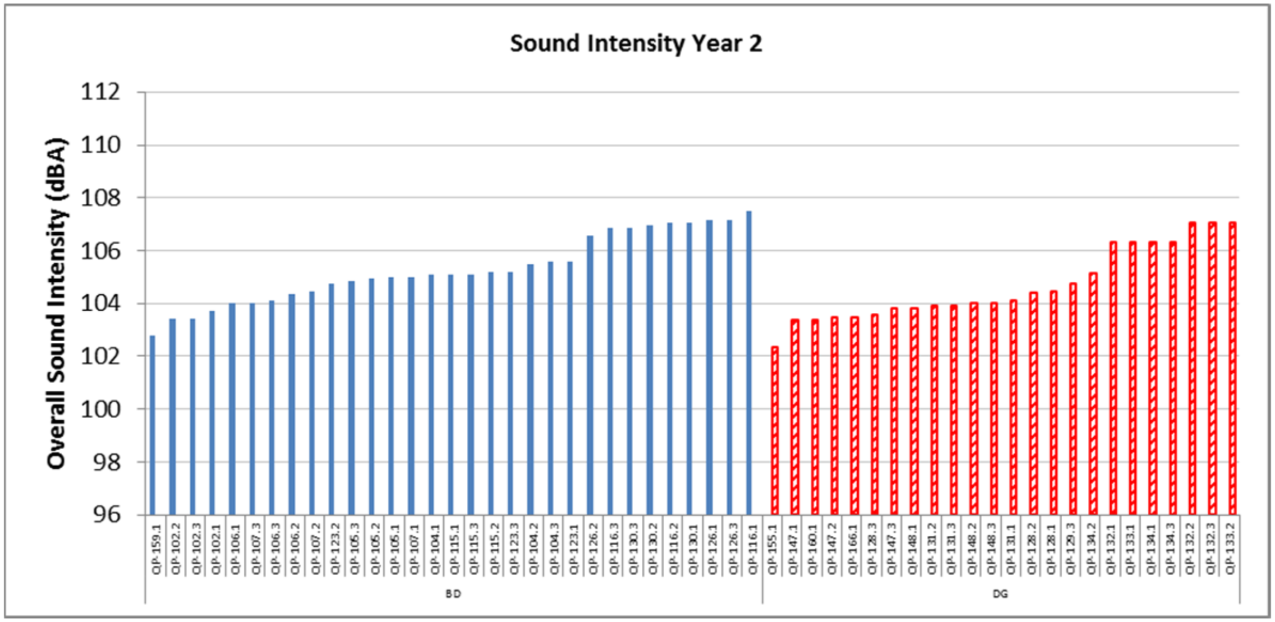


Figure A.1: On-board Sound Intensity levels of all sections as measured in Year 1.



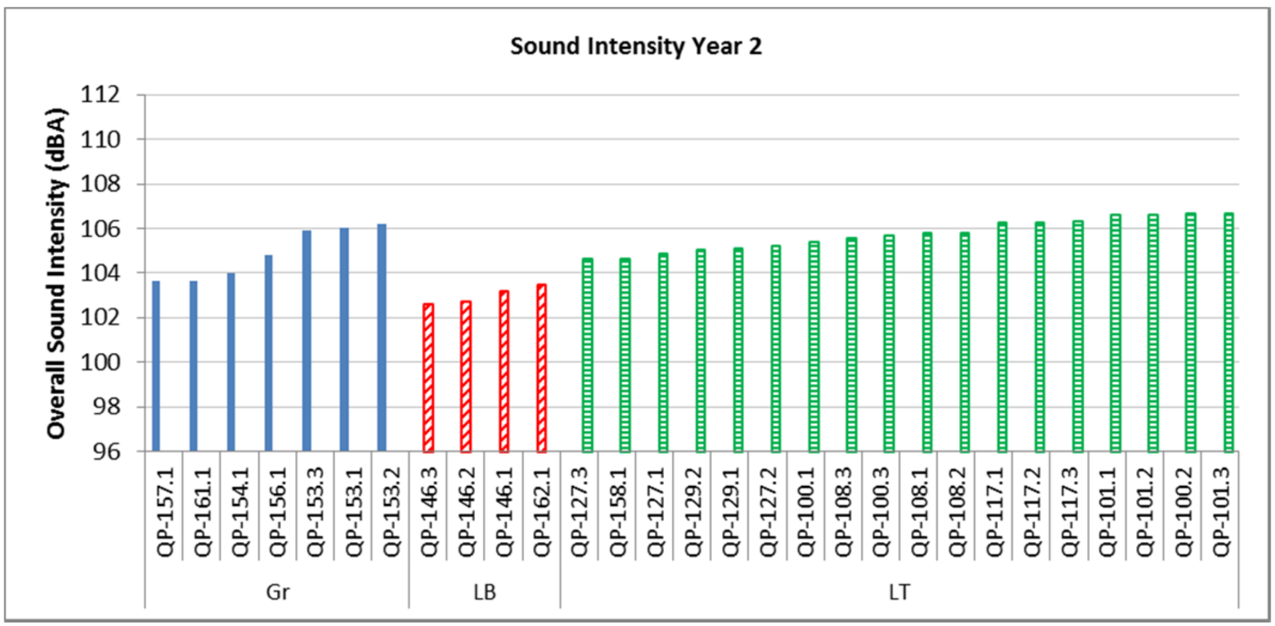


Figure A.2: On-board Sound Intensity levels of all sections as measured in Year 2.

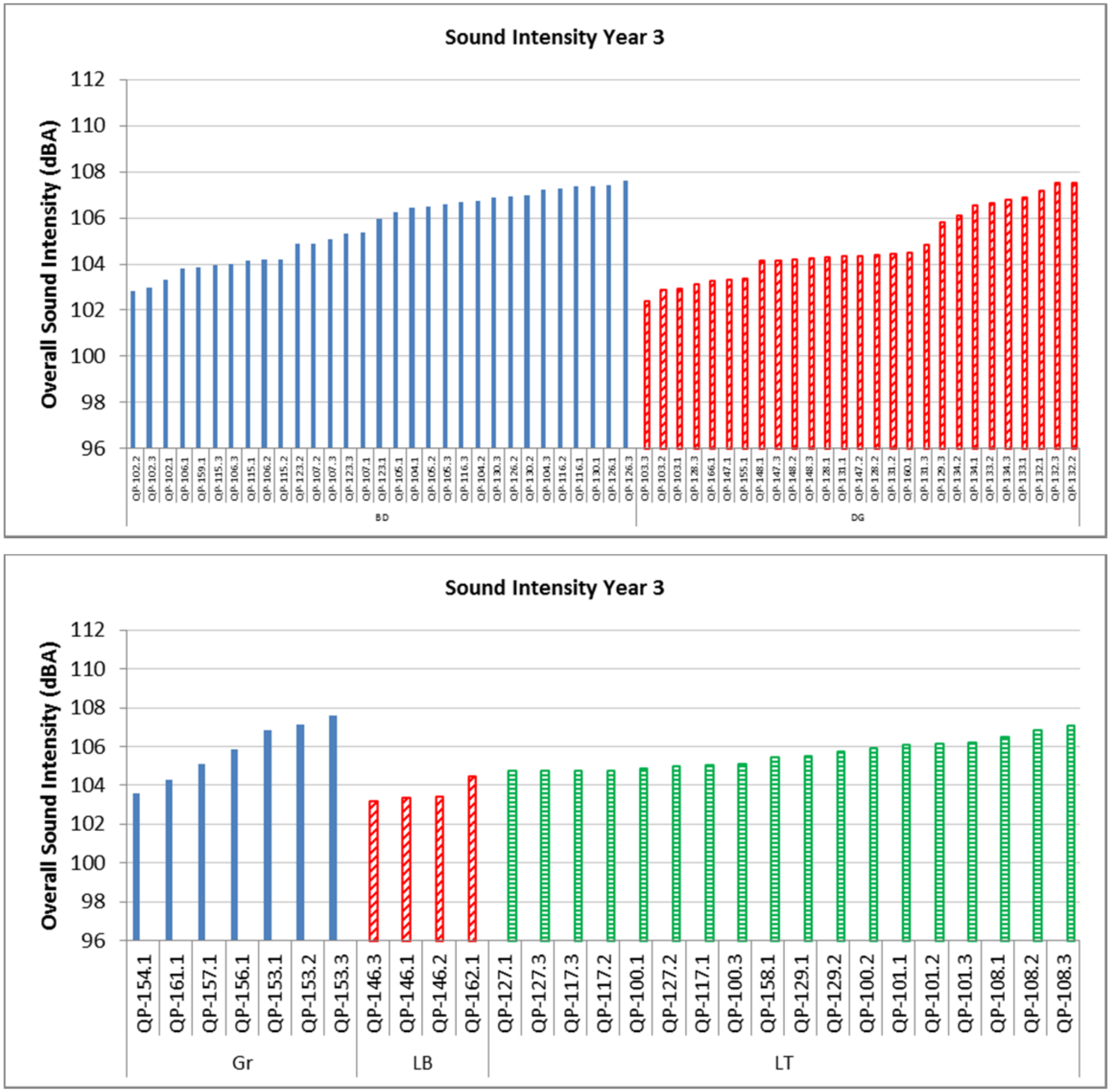


Figure A.3: On-board Sound Intensity levels of all sections as measured in Year 3.

APPENDIX B: CORRELATION OF SRTT#1 AND SRTT#4

In order to continue development of time series data for tire/pavement noise across many years and at different times, a set of experimental noise measurements were performed for the new tire, SRTT#4, used in this study. Twenty different road sections with different noise characteristics were selected, and the pavement noise was measured with both the new and old tires.

Measurements for the correlation experiment were made one after the other with each tire on each section, which consist of concrete and undoweled jointed PCC pavements, to minimize any effects on the results from temperature-induced curl and joint opening. Table B.1 shows the average and the standard deviation for the experimental noise sections.

Table B.1: Average and Standard Deviation of Overall Sound Intensity for Experimental Noise Sections Measured by SRTT#1 and SRTT#4

Section ID	Pavement Type	TIRE			
		SRTT#1		SRTT#4	
		Mean	Std.Dev	Mean	Std.Dev
ES-1	AC	101.8	0.06	101.1	0.38
ES-2	AC	101.8	0.05	101.8	0.12
ES-3	AC	101.1	0.16	100.9	0.09
ES-4	AC	102.0	0.18	101.9	0.17
ES-5	AC	101.9	0.06	101.3	0.12
ES-6	AC	102.0	0.34	101.5	0.24
ES-7	AC	103.3	0.12	103.0	0.16
ES-8	AC	103.4	0.31	102.8	0.18
ES-9	AC	102.4	0.25	102.4	1.10
ODR-N	AC	102.2	0.03	102.3	0.18
ODR-S	AC	102.9	0.04	103.1	0.18
RD105-S	AC	103.9	0.17	104.2	0.05
RD105-N	AC	103.4	0.12	103.3	0.04
QP-100	PCC	105.7	0.04	105.4	0.14
QP-101	PCC	107.1	0.06	106.7	0.04
QP-102	PCC	104.0	0.37	103.4	0.59
QP-115	PCC	105.7	0.09	105.7	0.30
RD32a-E	PCC	106.9	0.04	106.6	0.23
RD32a-W1	PCC	106.0	0.06	105.7	0.07
RD32a-W2	PCC	105.2	0.05	104.9	0.06

The data tabulated in Table B.1 are shown in Figure B.1, where it can be seen that that for the combined asphalt and concrete sections the results of the noise measurements in terms of overall OBSI with SRTT#1 are higher than those with SRTT#4, with an average difference of 0.2 and a standard deviation of 0.4. However, the measurements with the two tires are highly correlated with a coefficient of correlation of 0.95 (Figure B.2). Figure B.2(a) shows the correlation of SRTT#4 with SRTT#1 for all calibration sections together. Figure B.2(c) shows the correlation coefficient of sound intensities measured with SRTT#1 compared to sound intensities measured with all other tires for asphalt and concrete test sections together. As can be seen in Figure B.2(b), there is no apparent effect of pavement type on the correlation between SRTT#4 and SRTT#1. However, in keeping with practice in the previous two years, a tire conversion equation based only on the concrete sections was used for this report. The correlation shown in Figure B.2(b) for concrete pavement was used to convert results for overall OBSI to equivalent results for SRTT#1 in this study. This practice will be re-evaluated in the fourth year study to determine whether a tire conversion equation for that year's test tire using both surface types can be used without any bias towards one or the other surface type.

The results of measurements with the two tires were also compared for each frequency for both the asphalt and concrete calibration sections at one-third octave band levels, as shown Figure B.3. The results show that SRTT#1 generally produces higher noise values than SRTT#4 at frequencies of 1,000 Hz and above and similar values at frequencies lower than 1,000 Hz.

A linear relation between SRTT#1 and SRTT#4 from the concrete sections for each frequency exhibits a high correlation.

Figure B.4 shows the frequency-by-frequency correlation equations based on the concrete sections only used for this study. The linear conversion equations for the overall OBSI and each frequency are shown in Table B.2.

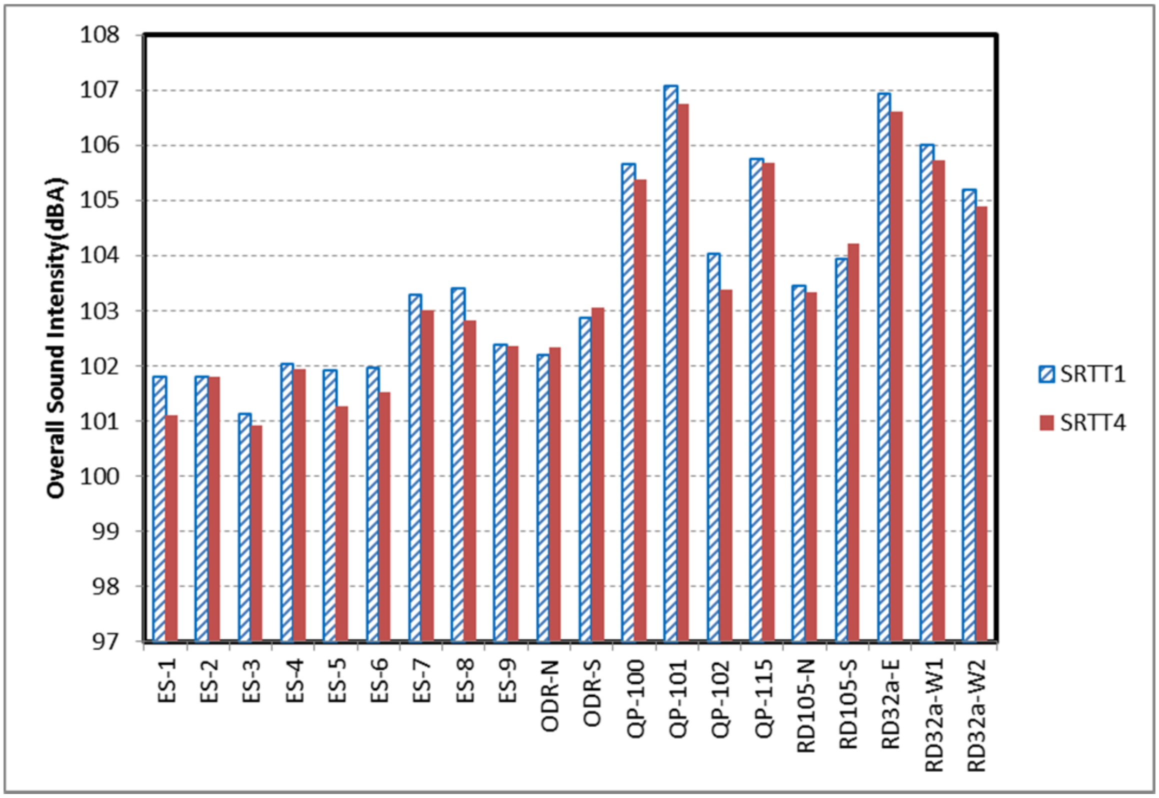
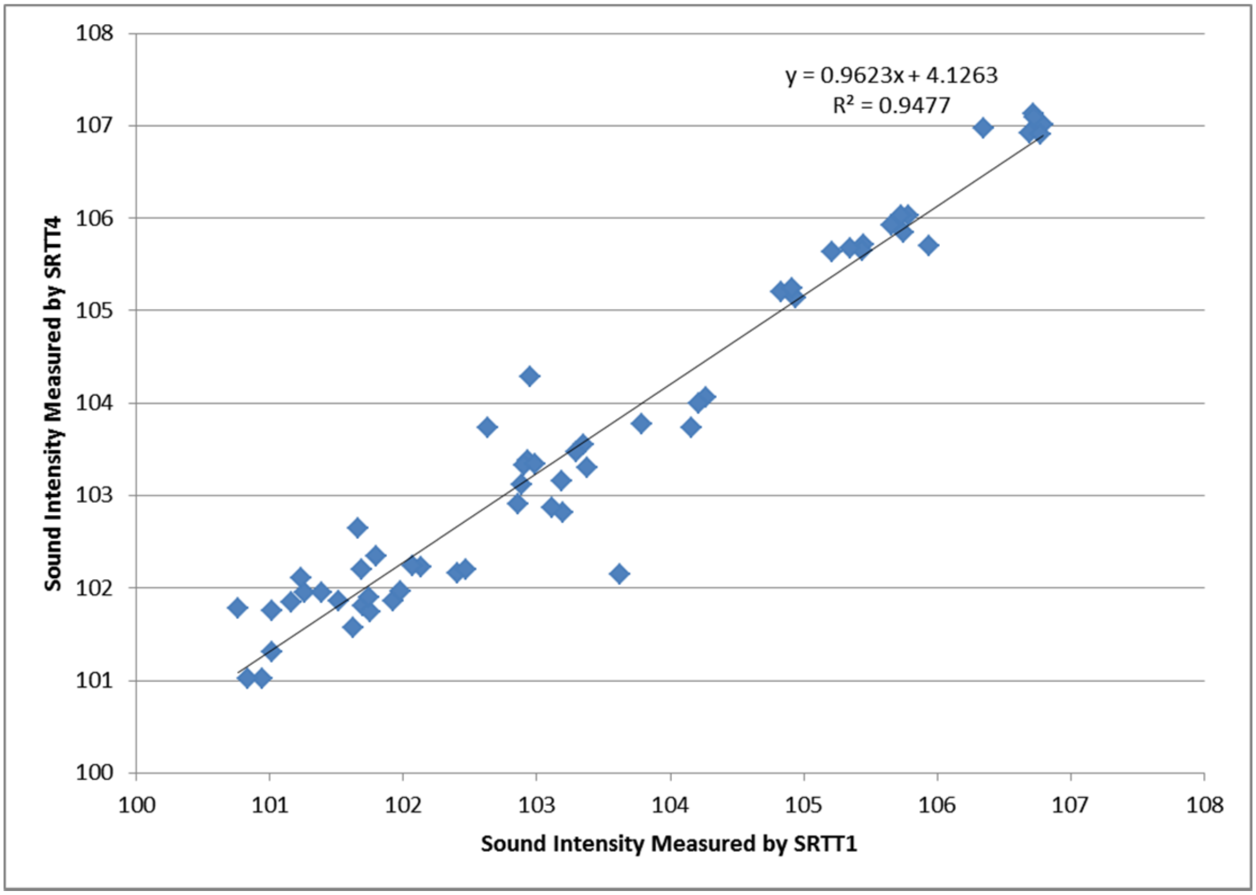
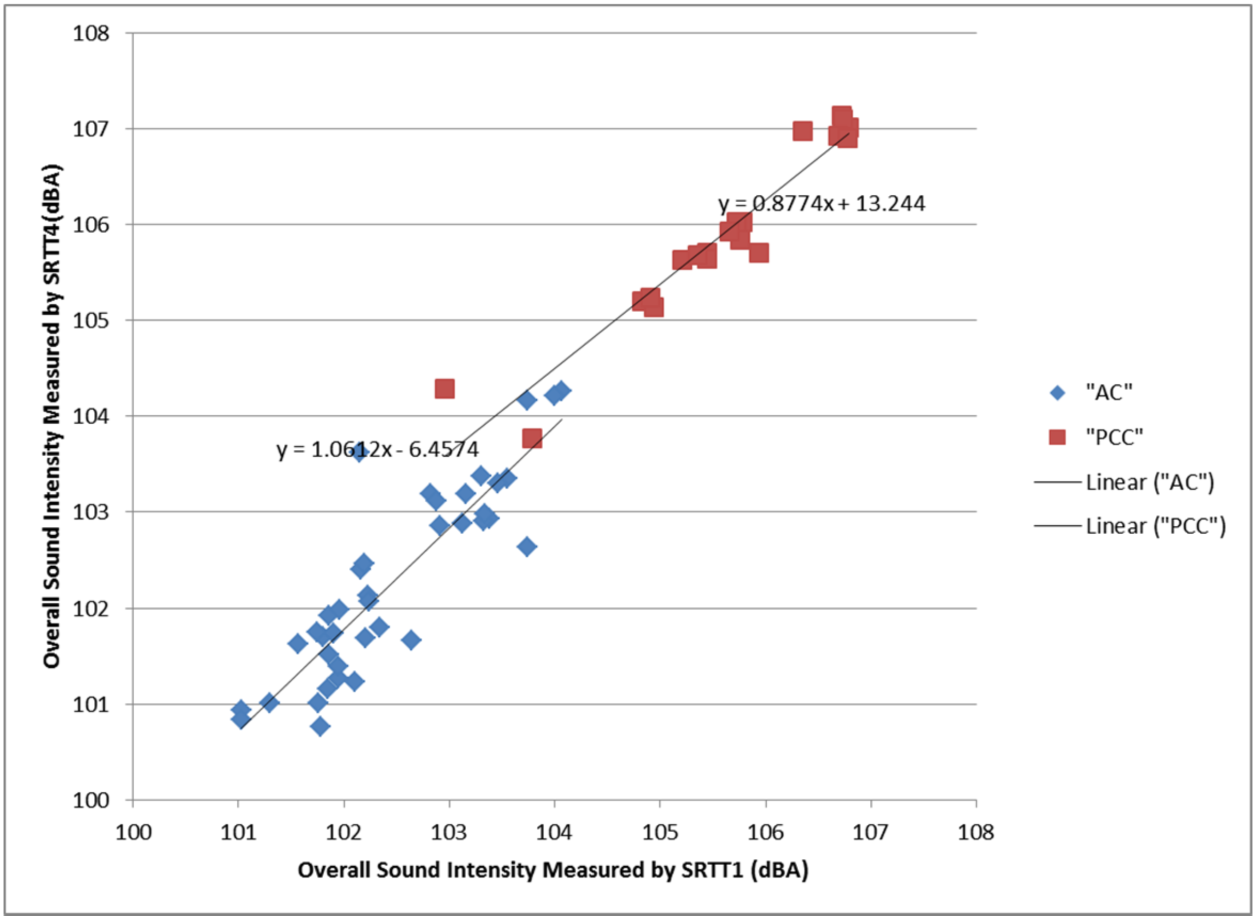


Figure B.1: Average overall sound intensities measured by SRTT#1 and SRTT#4 for different test sections.



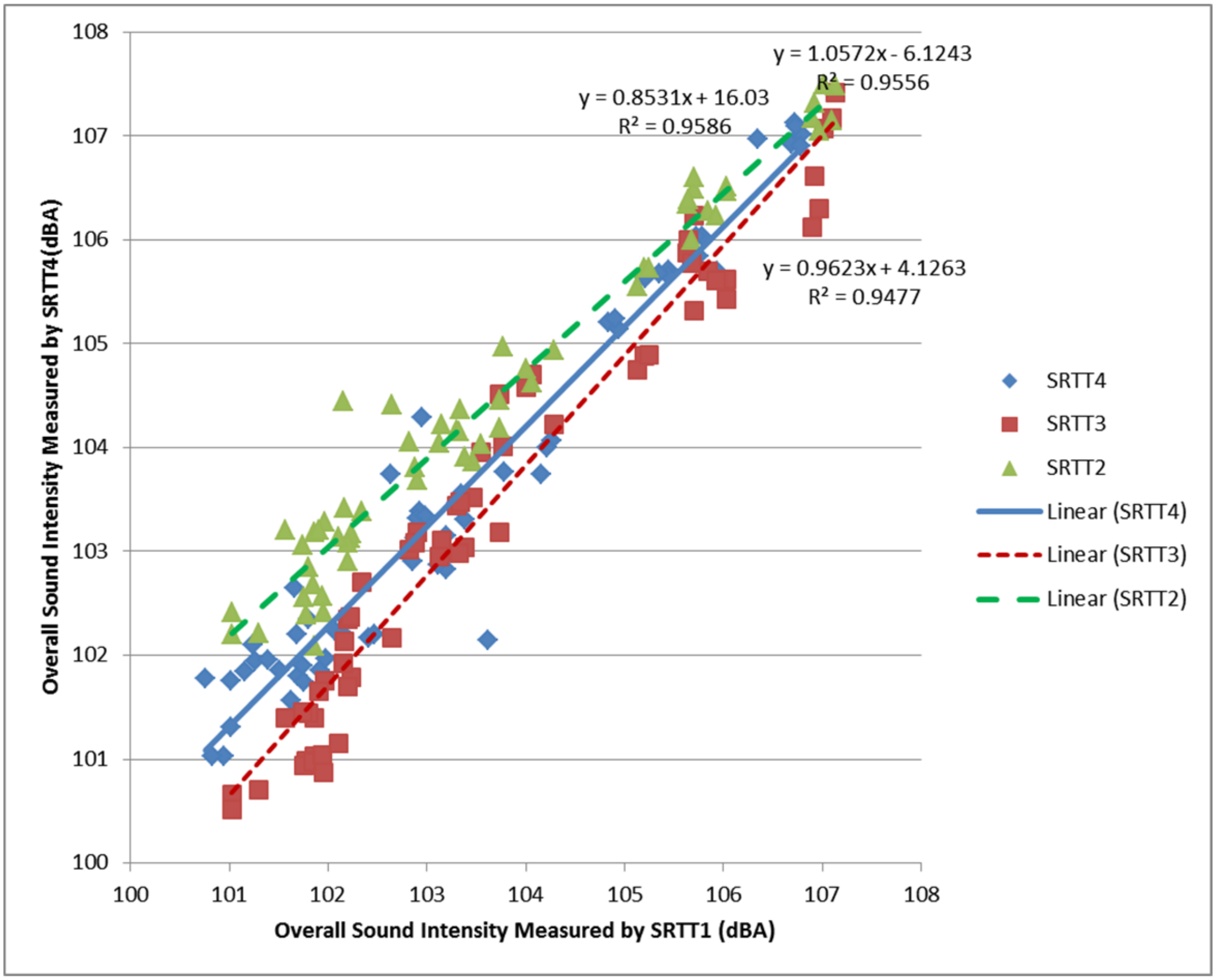
(a)

(continued below)



(b)

(continued below)

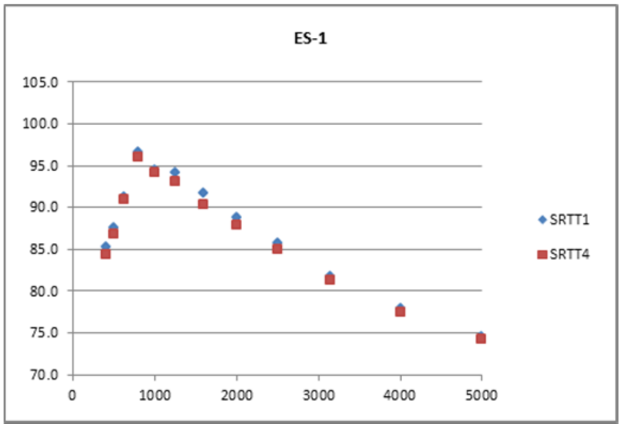


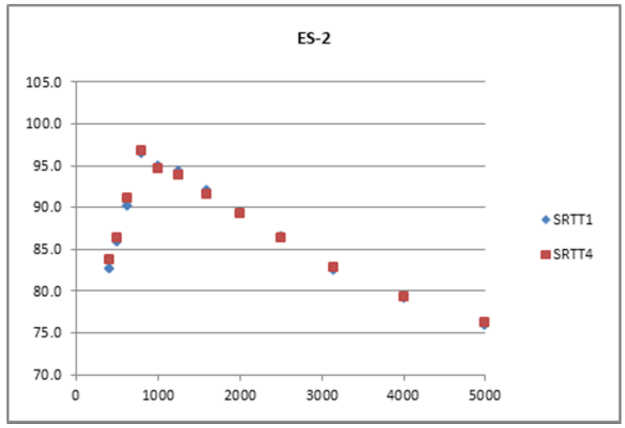
(c)

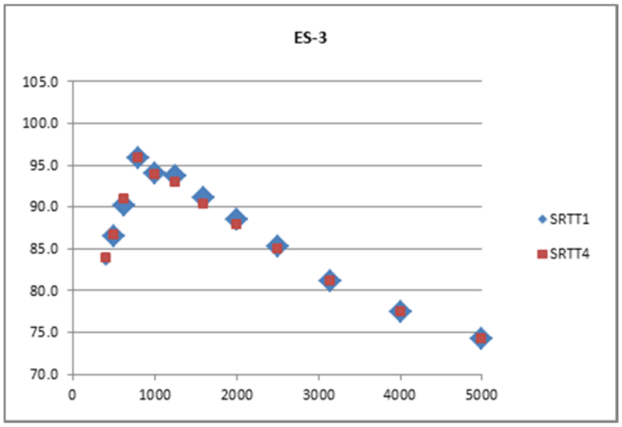
Figure B.2: Correlation between sound intensities measured by different tires: (a) SRTT#1 and SRTT#4 for all asphalt and concrete sections, (b) for asphalt and concrete sections separately, and (c) SRTT#1 and all other test tires for asphalt and concrete sections.

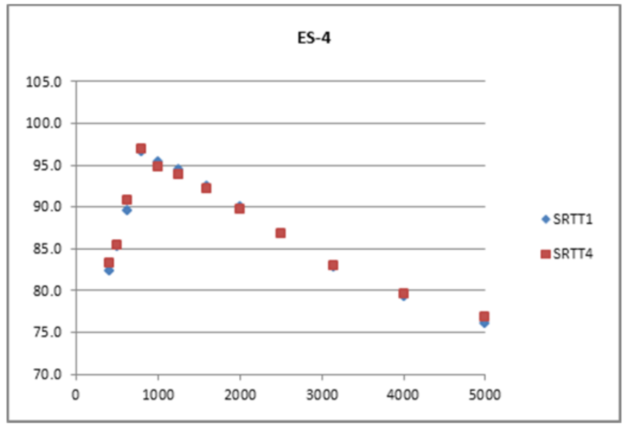
Table B.2: Spectral and Overall Correction for Test Tire and Sound Analyzer (OBSI values corrected for analyzer and tire)
Note: OBSI(SRTT#1) = A+B*OBSI(SRTT#X) or OBSI(Harmonie) = A+B*OBSI(Larson Davis)

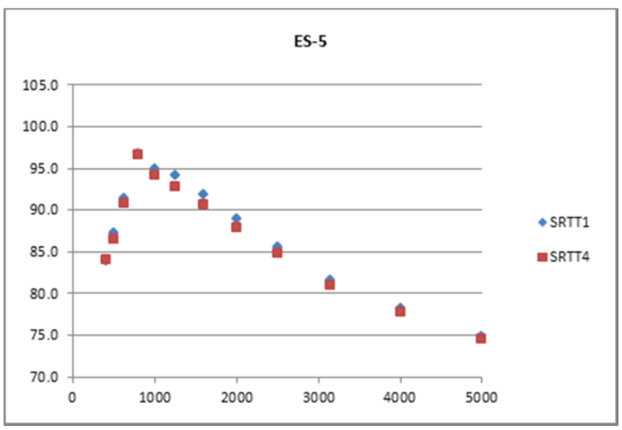
Parameter	Frequency												Overall
	400	500	630	800	1,000	1,250	1,600	2,000	2,500	3,150	4,000	5,000	
SRTT#2 to SRTT#1													
A	12.92	-4.83	-0.13	-3.61	12.85	2.34	-3.66	-6.17	2.15	-1.35	-0.46	0.97	-20.54
B	0.86	1.05	1	1.03	0.86	0.97	1.03	1.05	0.97	1.01	1	0.99	1.19
R^2	0.58	0.93	0.96	0.95	0.65	0.94	0.95	0.93	0.92	0.95	0.96	0.92	0.94
SRTT#3 to SRTT#1													
A	5.03	-33.53	-16.82	-16.27	-1.01	-1.04	9.1	1.15	0.74	10.46	7.62	2.03	-9.28
B	0.95	1.37	1.18	1.16	1.01	1.01	0.9	0.99	0.99	0.87	0.91	0.97	1.09
R^2	0.75	0.9	0.92	0.95	0.94	0.92	0.96	0.96	0.93	0.93	0.93	0.94	0.96
SRTT#4 to SRTT#1													
A	1.86	-6.86	0.12	3.33	22.84	6.34	17.38	10.31	7.52	7.68	6.68	8.38	13.24
B	0.98	1.08	1.00	0.97	0.77	0.94	0.83	0.90	0.92	0.91	0.92	0.90	0.88
R^2													
Larson Davis to Harmonie Analyzer													
A	14.06	0.52	1.39	5.03	-0.28	3.6	2.27	1.7	1.34	1.91	2.33	4.34	2.19
B	0.83	0.99	0.98	0.95	1	0.96	0.97	0.98	0.98	0.98	0.97	0.94	0.98
R^2	0.67	0.95	0.95	0.95	0.97	0.95	0.97	0.96	0.95	0.92	0.92	0.89	0.97

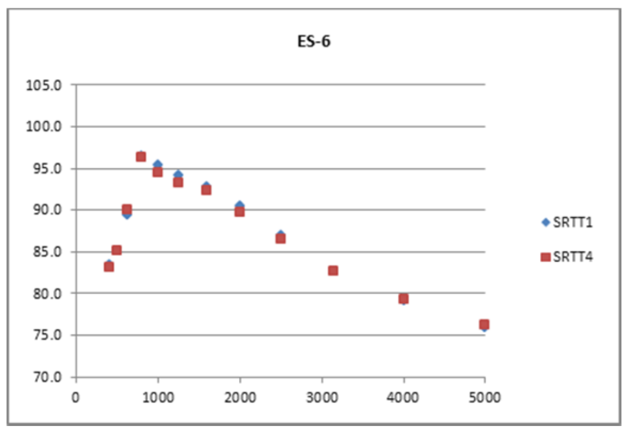

ES-1
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

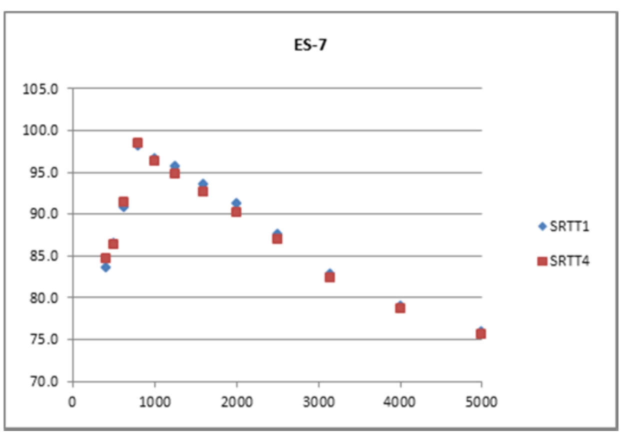

ES-2
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

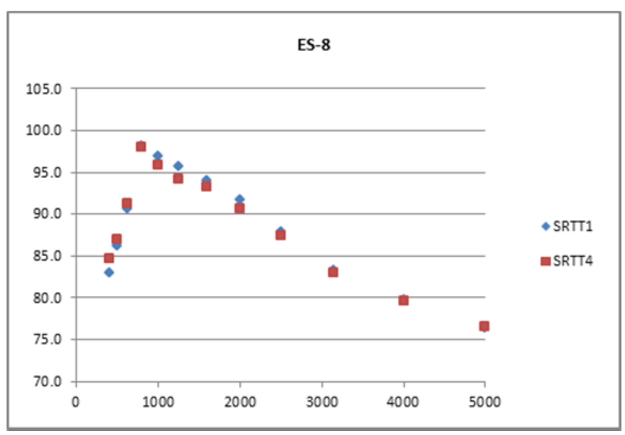

ES-3
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

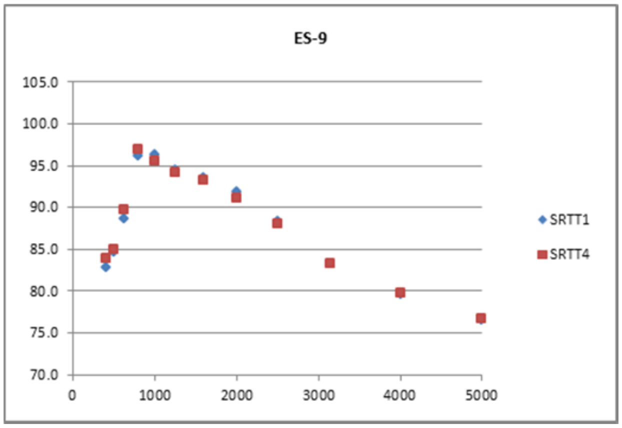

ES-4
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

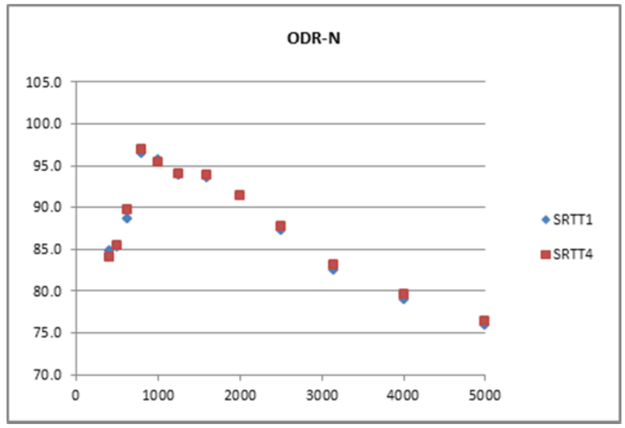

ES-5
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

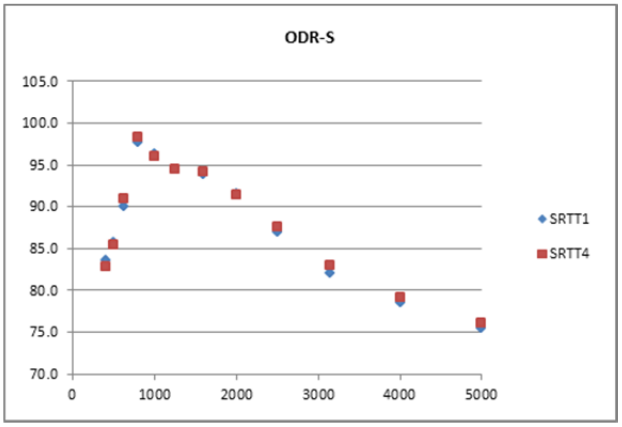

ES-6
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

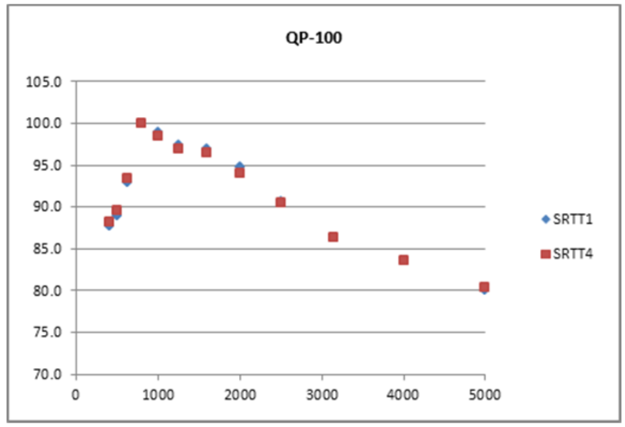

ES-7
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

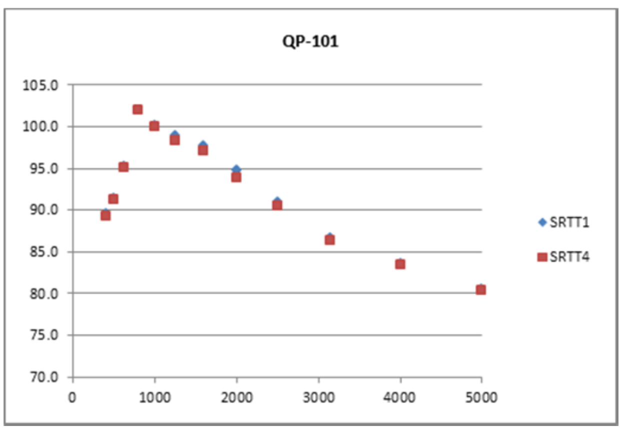

ES-8
105.0
100.0
95.0
90.0
85.0
80.0
75.0
70.0
0
1000
2000
3000
4000
5000
SRTT1
SRTT4

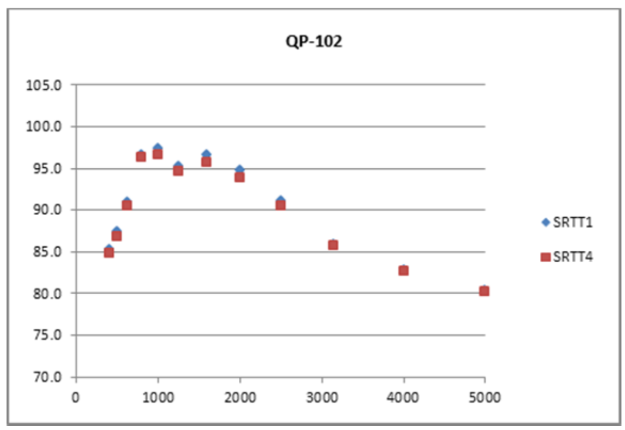

ES-9
SRTT1
SRTT4

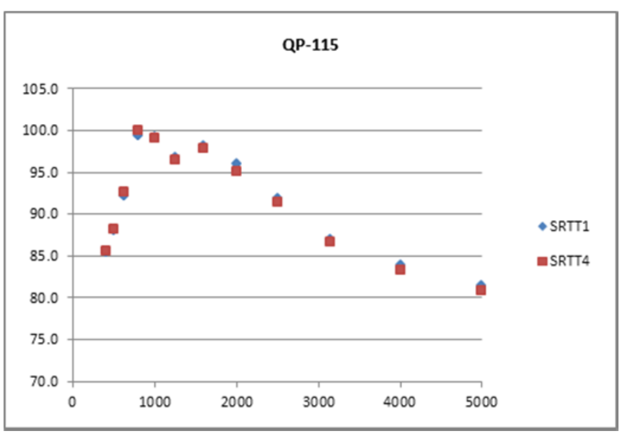

ODR-N
SRTT1
SRTT4

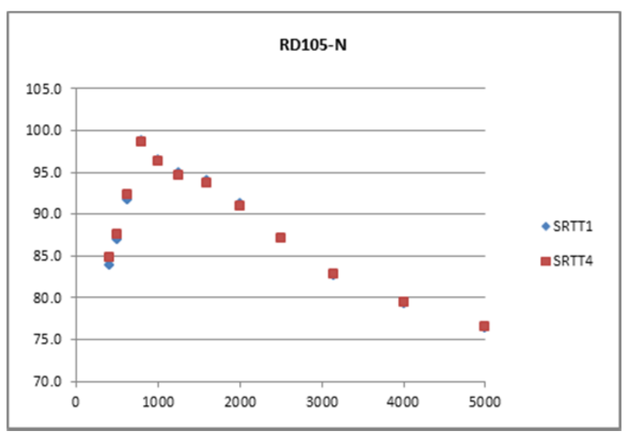

ODR-S
SRTT1
SRTT4


QP-100
SRTT1
SRTT4


QP-101
SRTT1
SRTT4


QP-102
SRTT1
SRTT4


QP-115
SRTT1
SRTT4


RD105-N
SRTT1
SRTT4

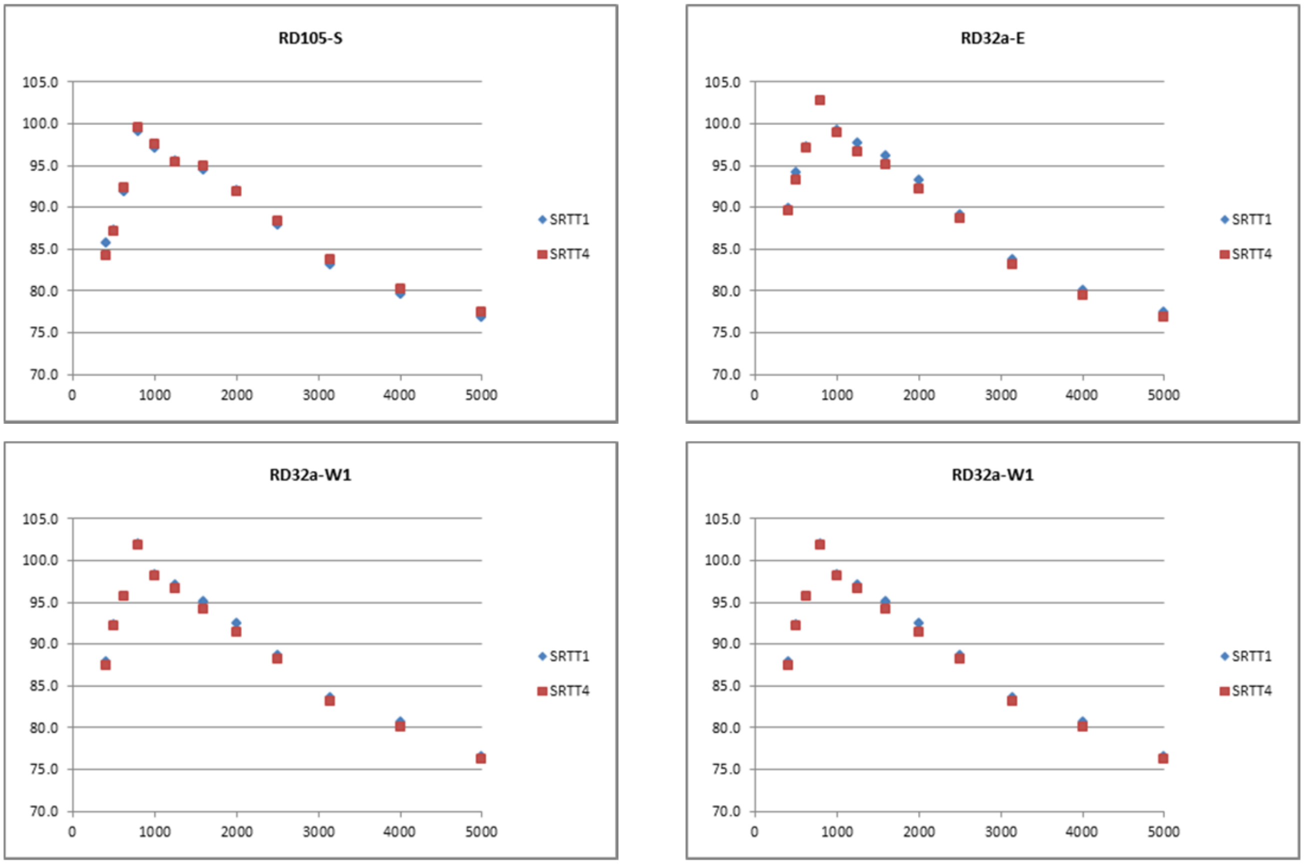
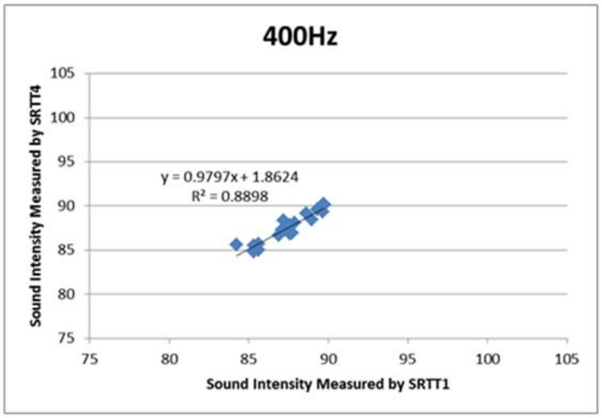
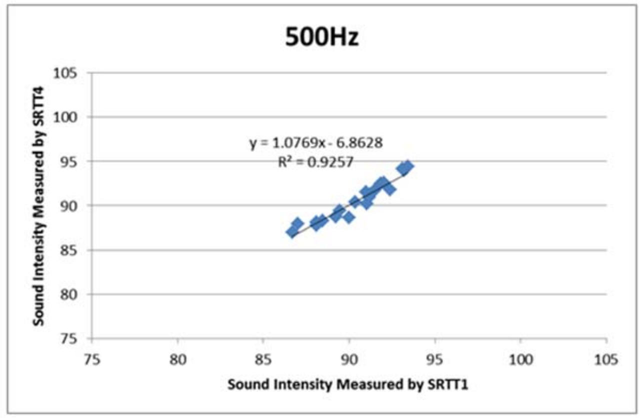
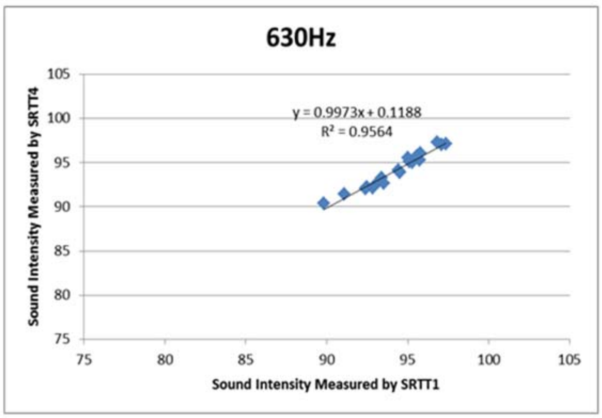
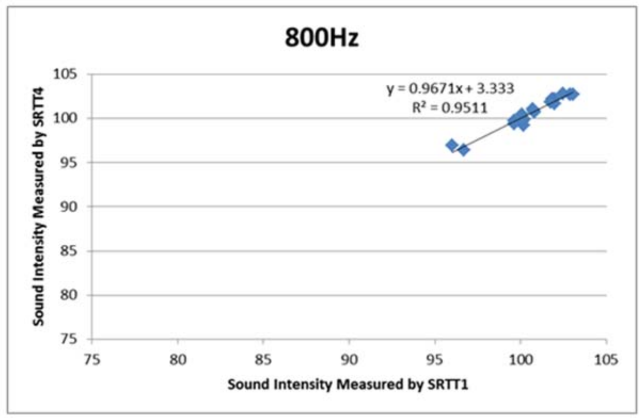


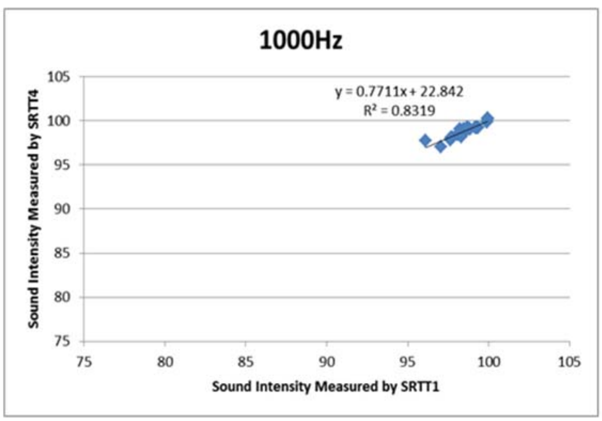
Figure B.3: Relationship between sound intensities at one-third octave bands for SRTT#1 and SRTT#4 for all tire calibration test sections.

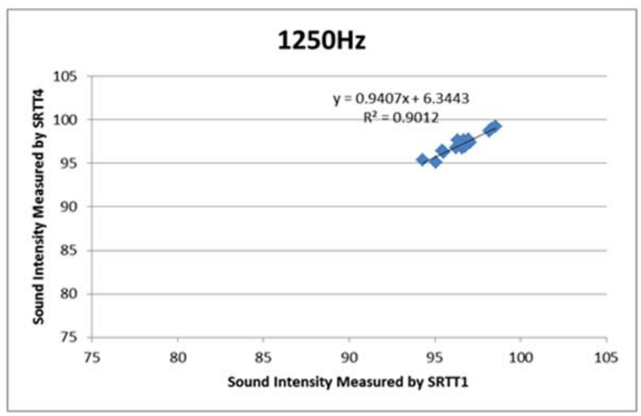

400Hz
y = 0.9797x + 1.8624
R² = 0.8898
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105

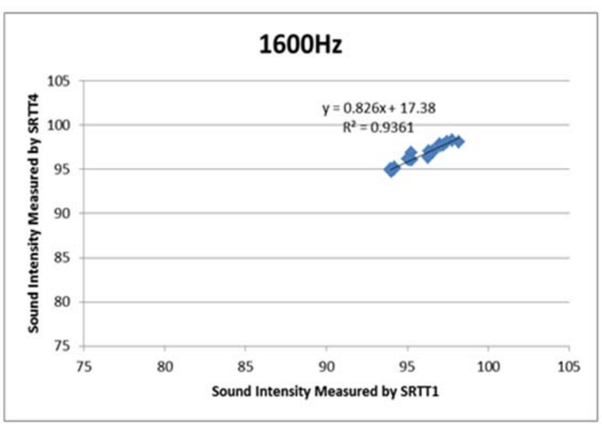

500Hz
y = 1.0769x - 6.8628
R² = 0.9257
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105

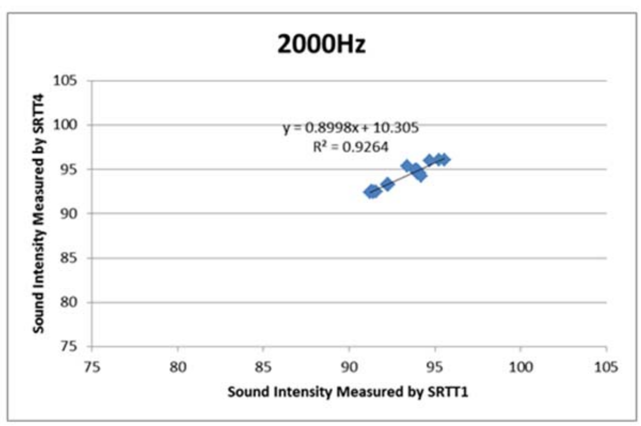

630Hz
y = 0.9973x + 0.1188
R² = 0.9564
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105


800Hz
y = 0.9671x + 3.333
R² = 0.9511
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105


1000Hz
y = 0.7711x + 22.842
R² = 0.8319
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105


1250Hz
y = 0.9407x + 6.3443
R² = 0.9012
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105


1600Hz
y = 0.826x + 17.38
R² = 0.9361
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105


2000Hz
y = 0.8998x + 10.305
R² = 0.9264
Sound Intensity Measured by SRTT4
Sound Intensity Measured by SRTT1
105
100
95
90
85
80
75
75
80
85
90
95
100
105

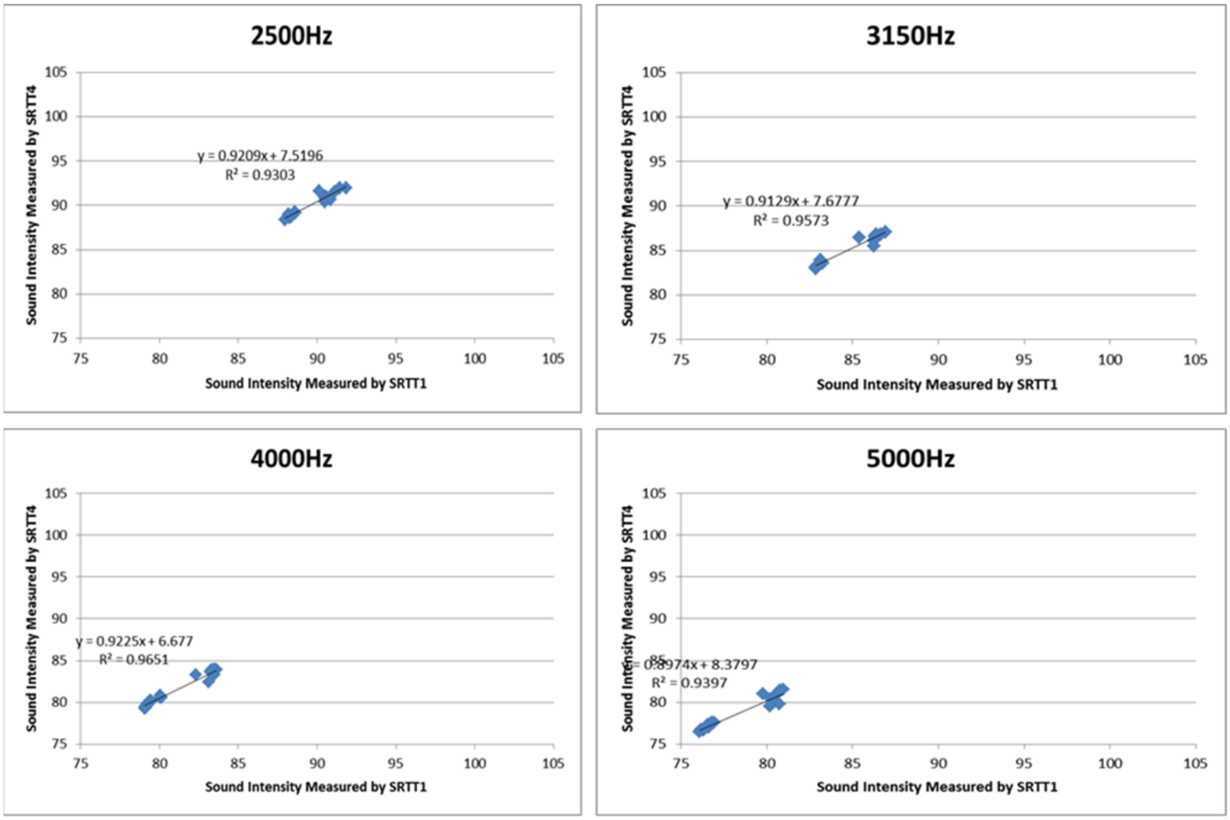


Figure B.4: Correlation between sound intensities at one-third octave bands for SRTT#1 and SRTT#4 for concrete tire calibration test sections.

APPENDIX C: SUMMARY TABLE AND SELECTED FIGURES WITH UNCORRECTED OBSI DATA

This appendix presents selected tables and figures from the main body of this report that have been remade using data without corrections for tire type and noise analyzer. The numbering and captions for the tables and figures are the same as those in the main body of the report to facilitate comparison.

Section ID	Location: Dist-Cnty -Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Condition[3]	Test Tire Year 1	Uncorr. OBSI Year 1	Test Tire Year 2	Uncorr. OBSI Year 2	Test Tire Year 3	Uncorr. OBSI Year 3	Corr. to SRTT #1 OBSI Year 1	Corr. to SRTT #1 OBSI Year 2	Corr. to SRTT #1 OBSI Year 3
QP-117.1	04CC80W10.3	4 of 4	LT	2007	2007	New	SRTT #2	104.7	SRTT #3	106.4	SRTT #4	104.6	103.1	106.3	105.0
QP-117.2	04CC80W10.2	4 of 4	LT	2007	2007	New	SRTT #2	104.4	SRTT #3	106.4	SRTT #4	104.3	102.7	106.3	104.7
QP-117.3	04CC80W10.1	4 of 4	LT	2007	2007	New	SRTT #2	104.5	SRTT #3	106.5	SRTT #4	104.3	102.9	106.4	104.7
QP-142.1	03NEV80W1.0	2 of 2	LT	2008	2008	New	SRTT #2	107.9	SRTT #3	113.3	SRTT #4	111.6	104.9	111.4	111.1
QP-142.2	03NEV80W0.9	2 of 2	LT	2008	2008	New	SRTT #2	107.6	SRTT #3	113	SRTT #4	111.2	104.5	111.2	110.8
QP-142.3	03NEV80W0.8	2 of 2	LT	2008	2008	New	SRTT #2	107.1	SRTT #3	114.3	SRTT #4	111.3	103.9	112.6	110.9
QP-100.1	03Yol113N3.0	2 of 2	LT	1976	1976	Aged	SRTT #2	104.9	SRTT #3	105.7	SRTT #4	104.4	103.1	105.3	104.9
QP-100.2	03Yol113N3.1	2 of 2	LT	1976	1976	Aged	SRTT #2	106.4	SRTT #3	107.1	SRTT #4	105.6	104.7	106.8	105.9
QP-100.3	03Yol113N3.2	2 of 2	LT	1976	1976	Aged	SRTT #2	105.5	SRTT #3	106.1	SRTT #4	104.6	103.7	105.6	105.1
QP-101.1	03Yol113N6.0	2 of 2	LT	1990	1990	Aged	SRTT #2	106.5	SRTT #3	107.1	SRTT #4	105.8	105.2	106.7	106.0
QP-101.2	03Yol113N6.1	2 of 2	LT	1990	1990	Aged	SRTT #2	106.8	SRTT #3	107.1	SRTT #4	105.9	105.5	106.7	106.1
QP-101.3	03Yol113N6.2	2 of 2	LT	1990	1990	Aged	SRTT #2	106.5	SRTT #3	107.2	SRTT #4	105.9	105.2	106.8	106.2
QP-127.1	04SCL85S21.5L1	1 of 3	LT	1965	1965	Aged	SRTT #2	104.7	SRTT #3	104.7	SRTT #4	104.2	103.2	104.6	104.7
QP-127.2	04SCL85S21.4L1	1 of 3	LT	1965	1965	Aged	SRTT #2	105.2	SRTT #3	105.1	SRTT #4	104.5	103.7	105.1	105.0
QP-127.3	04SCL85S21.3L1	1 of 3	LT	1965	1965	Aged	SRTT #2	104.7	SRTT #3	104.5	SRTT #4	104.2	103.1	104.5	104.7
QP-129.1	06FRE180W55.7	3 of 3	LT	2008	2008	Aged	SRTT #2	105	SRTT #3	105.1	SRTT #4	105.1	103.6	105	105.5
QP-129.2	06FRE180W55.6	3 of 3	LT	2008	2008	Aged	SRTT #2	105.1	SRTT #3	105	SRTT #4	105.4	103.7	104.8	105.7
QP-158.1	06Ker58E109.5	2 of 2	LT	2003	2003	Aged	SRTT #2	105.9	SRTT #3	105.6	SRTT #4	105.1	103.6	104.4	105.4
QP-108.1	03Pla80E45.0	1 of 2	LT	1961	2004	Worn out	SRTT #2	106.9	SRTT #3	107.1	SRTT #4	106.2	104.5	105.8	106.5
QP-108.2	03Pla80E45.1	1 of 2	LT	1961	2004	Worn out	SRTT #2	107.1	SRTT #3	107.1	SRTT #4	106.7	104.7	105.7	106.8
QP-108.3	03Pla80E45.2	1 of 2	LT	1961	2004	Worn out	SRTT #2	106.5	SRTT #3	106.9	SRTT #4	106.9	103.9	105.5	107.0

Section ID	Location: Dist-Cnty -Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Condition[3]	Test Tire Year 1	Uncorr. OBSI Year 1	Test Tire Year 2	Uncorr. OBSI Year 2	Test Tire Year 3	Uncorr. OBSI Year 3	Corr. to SRTT #1 OBSI Year 1	Corr. to SRTT #1 OBSI Year 2	Corr. to SRTT #1 OBSI Year 3
QP-162.1	06Ker58E111.5	2 of 2	LB	2003	2003	Aged	SRTT #2	105	SRTT #3	104.1	SRTT #4	103.9	102.5	103	104.4
QP-146.1	04SM280N10.6	1 of 4	LB	1974	1974	Aged	SRTT #2	103.2	SRTT #3	103	SRTT #4	102.7	101.4	102.7	103.3
QP-146.2	04SM280N10.7	1 of 4	LB	1974	1974	Aged	SRTT #2	103	SRTT #3	102.5	SRTT #4	102.8	101.2	102.2	103.4
QP-146.3	04SM280N10.8	1 of 4	LB	1974	1974	Aged	SRTT #2	102.9	SRTT #3	102.4	SRTT #4	102.4	101.1	102.1	103.1
QP-109.1	03Nev80E22.6	1 of 2	LB	1989	1989	Worn out	SRTT #2	105.5	Not Tested	Not Tested	Not Tested		102.2		
QP-109.2	03Nev80E22.6	1 of 2	LB	1989	1989	Worn out	SRTT #2	105.9	Not Tested	Not Tested	Not Tested		102.7		
QP-109.3	03Nev80E22.6	1 of 2	LB	1989	1989	Worn out	SRTT #2	105.2	Not Tested	Not Tested	Not Tested		101.9		
QP-112.1	03Nev80W23.0	1 of 2	LB	1989	1989	Worn out	SRTT #2	105.5	Not Tested	Not Tested	Not Tested		102.1		
QP-112.2	03Nev80W22.9	1 of 2	LB	1989	1989	Worn out	SRTT #2	105.9	Not Tested	Not Tested	Not Tested		102.7		
QP-112.3	03Nev80W22.8	1 of 2	LB	1989	1989	Worn out	SRTT #2	107.2	Not Tested	Not Tested	Not Tested		104.1		
QP-115.1	03Yol505S13.1	2 of 2	BD	1977	1977	Aged	SRTT #2	105.3	SRTT #3	105.4	SRTT #4	103.6	104	105	104.2
QP-115.2	03Yol505S13.0	2 of 2	BD	1977	1977	Aged	SRTT #2	104.7	SRTT #3	105.5	SRTT #4	103.6	103.3	105	104.2
QP-115.3	03Yol505S12.9	2 of 2	BD	1977	1977	Aged	SRTT #2	104.7	SRTT #3	105.4	SRTT #4	103.4	103.3	105	103.9
QP-123.1	04ALA580E37.1	4 of 4	BD	1965	1965	Aged	SRTT #2	105.5	SRTT #3	105.9	SRTT #4	105.7	104.2	105.5	105.9
QP-123.2	04ALA580E37.2	4 of 4	BD	1965	1965	Aged	SRTT #2	105.3	SRTT #3	105	SRTT #4	104.4	104	104.6	104.9
QP-123.3	04ALA580E37.3	4 of 4	BD	1965	1965	Aged	SRTT #2	105.1	SRTT #3	105.5	SRTT #4	105.0	103.9	105.1	105.3
QP-137.1	04SON101N25.4L1	1 of 2	BD	1962	1962	Aged	SRTT #2	103.9	Not Tested	Not Tested	Not Tested		102.2		

Section ID	Location: Dist-Cnty -Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Condition[3]	Test Tire Year 1	Uncorr. OBSI Year 1	Test Tire Year 2	Uncorr. OBSI Year 2	Test Tire Year 3	Uncorr. OBSI Year 3	Corr. to SRTT #1 OBSI Year 1	Corr. to SRTT #1 OBSI Year 2	Corr. to SRTT #1 OBSI Year 3
QP-137.2	04SON101N25.5L1	1 of 2	BD	1962	1962	Aged	SRTT #2	104.6	Not Tested	Not Tested	Not Tested		103.1		
QP-137.3	04SON101N25.6L1	1 of 2	BD	1962	1962	Aged	SRTT #2	104.4	Not Tested	Not Tested	Not Tested		102.8		
QP-159.1	06Ker58E110.3	2 of 2	BD	2003	2003	Aged	SRTT #2	104.3	SRTT #3	103.4	SRTT #4	103.3	101.9	102.2	103.9
QP-102.1	03Yol113S5.5	2 of 2	BD	1976	1976	Worn out	SRTT #2	103.1	SRTT #3	104	SRTT #4	102.6	101.1	103.3	103.3
QP-102.2	03Yol113S5.4	2 of 2	BD	1976	1976	Worn out	SRTT #2	102.7	SRTT #3	103.7	SRTT #4	102.1	100.7	103	102.8
QP-102.3	03Yol113S5.3	2 of 2	BD	1976	1976	Worn out	SRTT #2	102.8	SRTT #3	103.7	SRTT #4	102.3	100.8	103	103.0
QP-104.1	03Sac50E3.2	1 of 5	BD	1971	1971	Worn out	SRTT #2	105.1	SRTT #3	105.4	SRTT #4	106.2	103.5	105	106.4
QP-104.2	03Sac50E3.2	1 of 5	BD	1971	1971	Worn out	SRTT #2	105.6	SRTT #3	105.8	SRTT #4	106.5	104.1	105.4	106.7
QP-104.3	03Sac50E3.2	1 of 5	BD	1971	1971	Worn out	SRTT #2	106	SRTT #3	105.9	SRTT #4	107.1	104.7	105.5	107.2
QP-105.1	03Sac50E4.0	1 of 4	BD	1971	1971	Worn out	SRTT #2	104.5	SRTT #3	105.3	SRTT #4	106.0	102.9	104.8	106.2
QP-105.2	03Sac50E4.1	1 of 4	BD	1971	1971	Worn out	SRTT #2	105.1	SRTT #3	105.2	SRTT #4	106.3	103.6	104.8	106.5
QP-105.3	03Sac50E4.2	1 of 4	BD	1971	1971	Worn out	SRTT #2	104.6	SRTT #3	105.1	SRTT #4	106.4	103	104.7	106.6
QP-106.1	03Sac50E10.5	1 of 5	BD	1973	1973	Worn out	SRTT #2	103.7	SRTT #3	104.3	SRTT #4	103.2	101.9	103.6	103.8
QP-106.2	03Sac50E10.6	1 of 5	BD	1973	1973	Worn out	SRTT #2	104	SRTT #3	104.7	SRTT #4	103.6	102.4	104.1	104.2
QP-106.3	03Sac50E10.7	1 of 5	BD	1973	1973	Worn out	SRTT #2	104.2	SRTT #3	104.4	SRTT #4	103.4	102.6	103.8	104.0
QP-107.1	03Sac80E13.6	5 of 5	BD	1973	1973	Worn out	SRTT #2	104.9	SRTT #3	105.3	SRTT #4	105.0	103.2	104.9	105.4
QP-107.2	03Sac80E13.7	5 of 5	BD	1973	1973	Worn out	SRTT #2	104.3	SRTT #3	104.7	SRTT #4	104.5	102.6	104.2	104.9
QP-107.3	03Sac80E13.8	5 of 5	BD	1973	1973	Worn out	SRTT #2	103.6	SRTT #3	104.2	SRTT #4	104.7	101.7	103.7	105.1
QP-113.1	03Yol80W22.9	1 of 3	BD	1965	1965	Worn out	SRTT #2	105.5	Not Tested	Not Tested	Not Tested		103.9		
QP-113.2	03Yol80W22.8	1 of 3	BD	1965	1965	Worn out	SRTT #2	105.9	Not Tested	Not Tested	Not Tested		104.4		

Section ID	Location:	Lane[1]	Texture Type[2]	Const.	Surfacing	Texture Condition[3]	Test Tire	Uncorr. OBSI	Test Tire	Uncorr. OBSI	Test Tire	Uncorr. OBSI	Corr. to SRTT #1 OBSI	Corr. to SRTT #1 OBSI	Corr. to SRTT #1 OBSI
	Dist-Cnty -Rte-Dir-PM			Year	Year		Year 1	Year 1	Year 2	Year 2	Year 3	Year 3	Year 1	Year 2	Year 3
QP-113.3	03Yol80W22.7	1 of 3	BD	1965	1965	Worn out	SRTT #2	105.2	Not Tested	Not Tested	Not Tested		103.6		
QP-116.1	04Sol80E32.0	1 of 3	BD	1946	1946	Worn out	SRTT #2	107.5	SRTT #3	108	SRTT #4	107.3	106.5	107.8	107.4
QP-116.2	04Sol80E32.1	1 of 3	BD	1946	1946	Worn out	SRTT #2	107.3	SRTT #3	107.5	SRTT #4	107.1	106.3	107.3	107.3
QP-116.3	04Sol80E32.2	1 of 3	BD	1946	1946	Worn out	SRTT #2	106.8	SRTT #3	107.3	SRTT #4	106.5	105.7	107	106.7
QP-126.1	04SCL85S21.5L3	3 of 3	BD	1965	1965	Worn out	SRTT #2	107.9	SRTT #3	107.2	SRTT #4	107.3	107	107.4	107.4
QP-126.2	04SCL85S21.4L3	3 of 3	BD	1965	1965	Worn out	SRTT #2	106.9	SRTT #3	106.6	SRTT #4	106.8	105.8	106.7	106.9
QP-126.3	04SCL85S21.3L3	3 of 3	BD	1965	1965	Worn out	SRTT #2	107.8	SRTT #3	107.2	SRTT #4	107.6	106.9	107.4	107.6
QP-130.1	11SD5S39.7	4 of 4	BD	1964	1964	Worn out	SRTT #2	108	SRTT #3	107.2	SRTT #4	107.3	106.9	107.3	107.4
QP-130.2	11SD5S39.6	4 of 4	BD	1964	1964	Worn out	SRTT #2	107.7	SRTT #3	107.1	SRTT #4	106.8	106.6	107.1	107.0
QP-130.3	11SD5S39.5	4 of 4	BD	1964	1964	Worn out	SRTT #2	107.9	SRTT #3	107	SRTT #4	106.7	106.8	107.1	106.9
QP-128.2	04SCL85N14.9	3 of 3	DG	1993	2006	New	SRTT #2	104.5	SRTT #3	104.3	SRTT #4	103.8	102.9	104.1	104.4
QP-128.3	04SCL85N14.10	3 of 3	DG	1993	2006	New	SRTT #2	103.4	SRTT #3	103.4	SRTT #4	102.4	101.6	103.1	103.1
QP-129.3	06FRE180W55.5	3 of 3	DG	2008	2008	New	SRTT #2	104.7	SRTT #3	104.7	SRTT #4	105.5	103.3	104.6	105.8
QP-147.1	04SM280N11.6	1 of 3	DG	1973	2007	New	SRTT #2	104	SRTT #3	103.3	SRTT #4	102.7	102.5	102.9	103.3
QP-147.2	04SM280N11.7	1 of 3	DG	1973	2007	New	SRTT #2	104.3	SRTT #3	103.4	SRTT #4	103.8	102.8	103	104.3
QP-147.3	04SM280N11.8	1 of 3	DG	1973	2007	New	SRTT #2	104.2	SRTT #3	103.8	SRTT #4	103.6	102.7	103.4	104.2
QP-103.1	03Yol50E0.2	1 of 4	DG	1969	2005	Aged	SRTT #2	101.8	Not Tested	Not Tested	Not Tested	102.2	99.8		102.9
QP-103.2	03Yol50E0.3	1 of 4	DG	1969	2005	Aged	SRTT #2	101.6	Not Tested	Not Tested	Not Tested	102.1	99.6		102.8
QP-103.3	03Yol50E0.4	1 of 4	DG	1969	2005	Aged	SRTT #2	101.5	Not Tested	Not Tested	Not Tested	101.6	99.4		102.4

Section ID	Location:	Lane[1]	Texture Type[2]	Const.	Surfacing	Texture Condition[3]	Test Tire	Uncorr. OBSI	Test Tire	Uncorr. OBSI	Test Tire	Uncorr. OBSI	Corr. to SRTT #1 OBSI	Corr. to SRTT #1 OBSI	Corr. to SRTT #1 OBSI
	Dist-Cnty -Rte-Dir-PM			Year	Year		Year 1	Year 1	Year 2	Year 2	Year 3	Year 3	Year 1	Year 2	Year 3
QP-114.1	04Sol80W18.7	2 of 4	DG	1949	1999	Aged	SRTT #2	104.1	Not Tested	Not Tested	Not Tested		102.3		
QP-114.2	04Sol80W18.6	2 of 4	DG	1949	1999	Aged	SRTT #2	104	Not Tested	Not Tested	Not Tested		102		
QP-114.3	04Sol80W18.5	2 of 4	DG	1949	1999	Aged	SRTT #2	104.4	Not Tested	Not Tested	Not Tested		102.6		
QP-128.1	04SCL85N14.8	3 of 3	DG	1993	2006	Aged	SRTT #2	104.6	SRTT #3	104.4	SRTT #4	103.7	103	104.2	104.3
QP-131.1	11SD8W15.5	1 of 3	DG	1985	1997	Aged	SRTT #2	106.6	SRTT #3	104.1	SRTT #4	103.8	105.3	103.7	104.3
QP-131.2	11SD8W15.6	1 of 3	DG	1985	1997	Aged	SRTT #2	106.4	SRTT #3	103.9	SRTT #4	103.9	105.1	103.6	104.4
QP-131.3	11SD8W15.7	1 of 3	DG	1985	1997	Aged	SRTT #2	106.5	SRTT #3	103.9	SRTT #4	104.4	105.2	103.6	104.8
QP-132.1	11SD805N2.1	5 of 5	DG	1975	1998	Aged	SRTT #2	106.8	SRTT #3	106.6	SRTT #4	107.0	105.4	106.3	107.1
QP-132.2	11SD805N2.2	5 of 5	DG	1975	1998	Aged	SRTT #2	107.8	SRTT #3	107.4	SRTT #4	107.4	106.6	107.2	107.5
QP-132.3	11SD805N2.3	5 of 5	DG	1975	1998	Aged	SRTT #2	107.3	SRTT #3	107.4	SRTT #4	107.4	106	107.3	107.5
QP-133.1	11SD805N2.3	4 of 4	DG	1975	1998	Aged	SRTT #2	107.6	SRTT #3	106.6	SRTT #4	106.7	106.5	106.4	106.9
QP-133.2	11SD805N2.4	4 of 4	DG	1975	1998	Aged	SRTT #2	Not Tested	SRTT #3	107.4	SRTT #4	106.4		107.3	106.6
QP-134.1	11SD905W5.2	2 of 2	DG	1975	2000	Aged	SRTT #2	106.3	SRTT #3	106.6	SRTT #4	106.3	105	106.4	106.5
QP-134.2	11SD905W5.1	2 of 2	DG	1975	2000	Aged	SRTT #2	106.2	SRTT #3	105.3	SRTT #4	105.8	104.9	104.9	106.1
QP-134.3	11SD905W5.0	2 of 2	DG	1975	2000	Aged	SRTT #2	107.3	SRTT #3	106.6	SRTT #4	106.6	106.2	106.4	106.8
QP-135.1	04SON101N25.4L2	2 of 2	DG	1962	2006	Aged	SRTT #2	104.9	Not Tested	Not Tested	Not Tested		103.4		
QP-135.2	04SON101N25.5L2	2 of 2	DG	1962	2006	Aged	SRTT #2	105	Not Tested	Not Tested	Not Tested		103.5		
QP-135.3	04SON101N25.6L2	2 of 2	DG	1962	2006	Aged	SRTT #2	105.2	Not Tested	Not Tested	Not Tested		103.7		

Section ID	Location: Dist-Cnty -Rte-Dir-PM	Lane[1]	Texture Type[2]	Const. Year	Surfacing Year	Texture Condition[3]	Test Tire Year 1	Uncorr. OBSI Year 1	Test Tire Year 2	Uncorr. OBSI Year 2	Test Tire Year 3	Uncorr. OBSI Year 3	Corr. to SRTT #1 OBSI Year 1	Corr. to SRTT #1 OBSI Year 2	Corr. to SRTT #1 OBSI Year 3
QP-148.1	04SM280N1.6	1 of 4	DG	1969	2001	Aged	SRTT #2	104.4	SRTT #3	103.7	SRTT #4	103.6	102.9	103.4	104.1
QP-148.2	04SM280N1.7	1 of 4	DG	1969	2001	Aged	SRTT #2	104.5	SRTT #3	103.9	SRTT #4	103.6	103	103.6	104.2
QP-148.3	04SM280N1.8	1 of 4	DG	1969	2001	Aged	SRTT #2	104.7	SRTT #3	103.9	SRTT #4	103.7	103.2	103.7	104.2
QP-155.1	06Ker58E110.6	2 of 2	DG	2003	2006	Aged	SRTT #2	104	SRTT #3	103	SRTT #4	102.7	101.2	101.7	103.4
QP-160.1	06Ker58E110.0	2 of 2	DG	2003	2006	Aged	SRTT #2	105.2	SRTT #3	104.2	SRTT #4	104.0	102.7	102.9	104.5
QP-166.1	06Ker58E111.7	2 of 2	DG	2003	2006	Aged	SRTT #2	104.2	SRTT #3	104.2	SRTT #4	102.6	101.7	103	103.3
QP-110.1	03Nev80E24.0	1 of 3	Gr	1989	1996	Aged	SRTT #2	105.3	Not Tested	Not Tested	Not Tested		102		
QP-110.2	03Nev80E24.1	1 of 3	Gr	1989	1996	Aged	SRTT #2	105.3	Not Tested	Not Tested	Not Tested		102		
QP-110.3	03Nev80E24.2	1 of 3	Gr	1989	1996	Aged	SRTT #2	105.2	Not Tested	Not Tested	Not Tested		101.9		
QP-111.1	03Nev80W24.2	1 of 2	Gr	1989	1996	Aged	SRTT #2	106.4	Not Tested	Not Tested	Not Tested		103.2		
QP-111.2	03Nev80W24.1	1 of 2	Gr	1989	1996	Aged	SRTT #2	106.3	Not Tested	Not Tested	Not Tested		103.1		
QP-111.3	03Nev80W24.0	1 of 2	Gr	1989	1996	Aged	SRTT #2	105.9	Not Tested	Not Tested	Not Tested		102.7		
QP-136.1	04SON101S27.3L2	2 of 2	Gr	1962	2006	Aged	SRTT #2	105.3	Not Tested	Not Tested	Not Tested		103.8		
QP-136.2	04SON101S27.2L2	2 of 2	Gr	1962	2006	Aged	SRTT #2	105.1	Not Tested	Not Tested	Not Tested		103.6		
QP-136.3	04SON101S27.1L2	2 of 2	Gr	1962	2006	Aged	SRTT #2	105.3	Not Tested	Not Tested	Not Tested		103.8		
QP-138.1	04SON101S27.3L1	1 of 2	Gr	1962	2006	Aged	SRTT #2	104.7	Not Tested	Not Tested	Not Tested		103.1		

Section ID	Location:	Lane[1]	Texture Type[2]	Const.	Surfacing	Texture Condition[3]	Test Tire	Uncorr. OBSI	Test Tire	Uncorr. OBSI	Test Tire	Uncorr. OBSI	Corr. to SRTT #1 OBSI	Corr. to SRTT #1 OBSI	Corr. to SRTT #1 OBSI
	Dist-Cnty -Rte-Dir-PM			Year	Year		Year 1	Year 1	Year 2	Year 2	Year 3	Year 3	Year 1	Year 2	Year 3
QP-138.2	04SON101S27.2L1	1 of 2	Gr	1962	2006	Aged	SRTT #2	104.6	Not Tested	Not Tested	Not Tested		103		
QP-138.3	04SON101S27.1L1	1 of 2	Gr	1962	2006	Aged	SRTT #2	103.5	Not Tested	Not Tested	Not Tested		101.7		
QP-153.1	10Mer99S17.5	1 of 2	Gr	1962	2006	Aged	SRTT #2	106.1	SRTT #3	106.1	SRTT #4	106.7	105.1	106.1	106.9
QP-153.2	10Mer99S17.4	1 of 2	Gr	1962	2006	Aged	SRTT #2	106.5	SRTT #3	106.3	SRTT #4	107.0	105.6	106.3	107.2
QP-153.3	10Mer99S17.3	1 of 2	Gr	1962	2006	Aged	SRTT #2	106.1	SRTT #3	106	SRTT #4	107.5	105.1	105.9	107.6
QP-154.1	06Ker58E110.2	2 of 2	Gr	2003	2006	Aged	SRTT #2	104.7	SRTT #3	104.9	SRTT #4	103.0	102.1	103.7	103.6
QP-156.1	06Ker58E111.2	2 of 2	Gr	2003	2006	Aged	SRTT #2	105.8	SRTT #3	105.7	SRTT #4	105.5	103.7	104.7	105.9
QP-157.1	06Ker58E111.4	2 of 2	Gr	2003	2006	Aged	SRTT #2	104.4	SRTT #3	104.4	SRTT #4	104.7	102.1	103.2	105.1
QP-161.1	06Ker58E110.4	2 of 2	Gr	2003	2006	Aged	SRTT #2	105.6	SRTT #3	104.3	SRTT #4	103.8	103.2	103.2	104.3

Notes:

1. Lane # of total lanes (Lane #1 is next to the median.)

2. Texture Type:

BD = burlap drag
DG = diamond ground
Gr = diamond grooved
LB = longitudinally broomed
LT = longitudinally tined

3. Texture Condition:

New = Sections that had been open to traffic for less than a year at the time of the first measurements
Aged = Sections where the texture could be observed in the wheelpaths
Worn out = Sections where the texture had been worn out in the wheelpaths by traffic

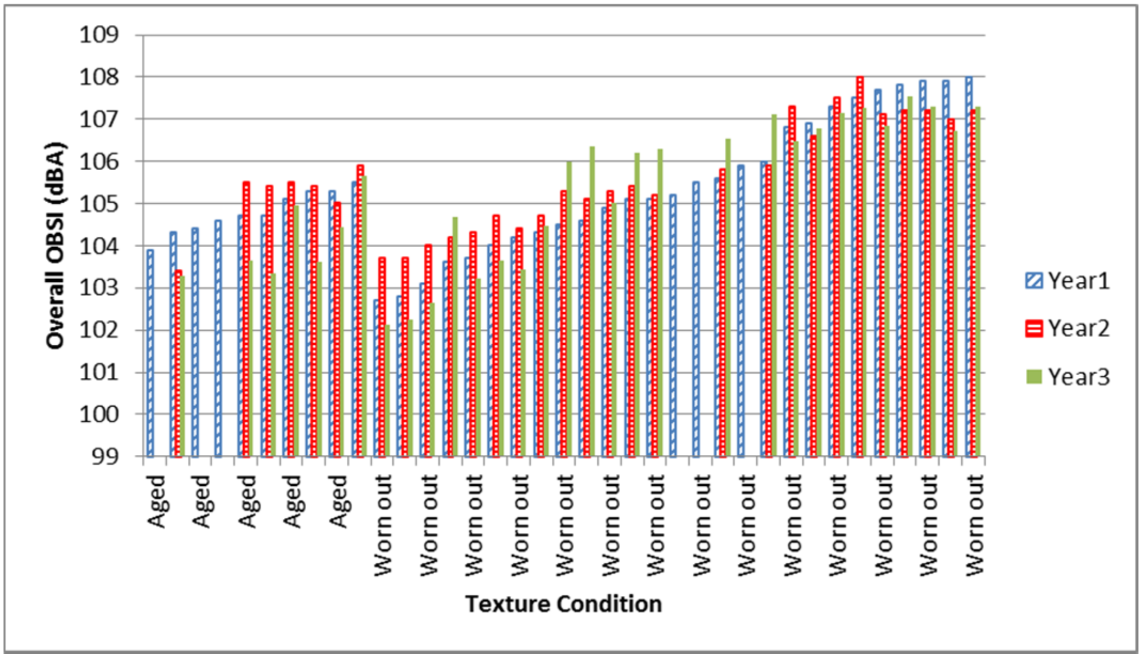


Figure C.1: Compare with Figure 3.23: Burlap drag Year 1, 2 and 3 OBSI results for *aged* and *worn out* texture sections (no *new* condition sections measured).

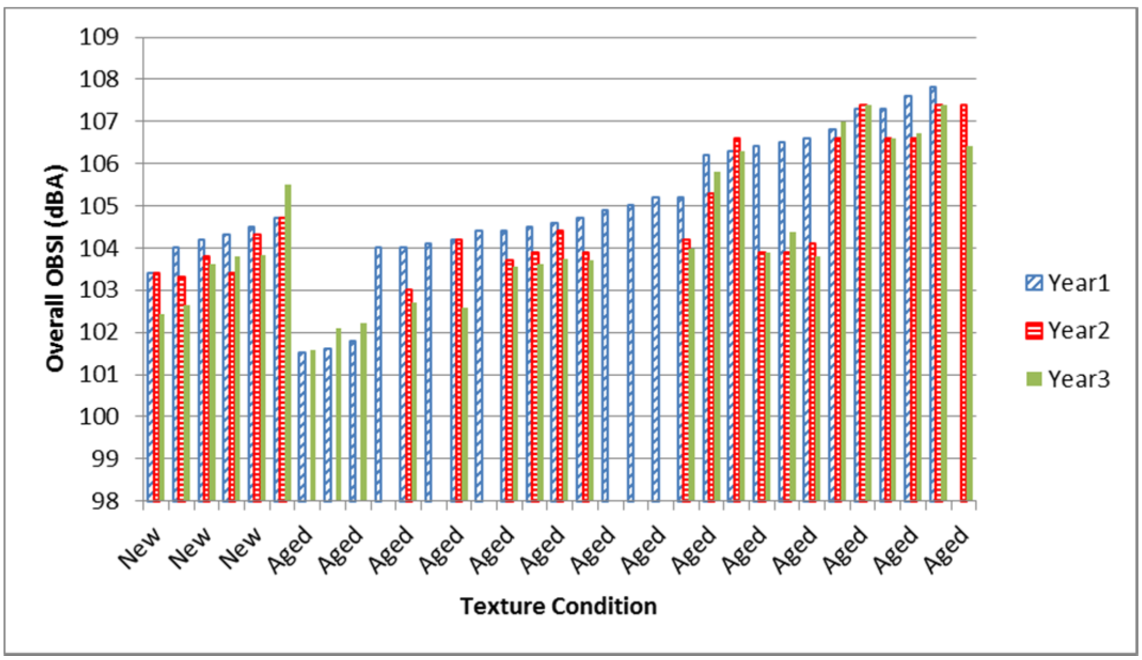


Figure C.2: Compare with Figure 3.26: Diamond-ground Year 1, 2, and 3 OBSI results for *new and aged* texture sections (no *worn out* condition sections measured).

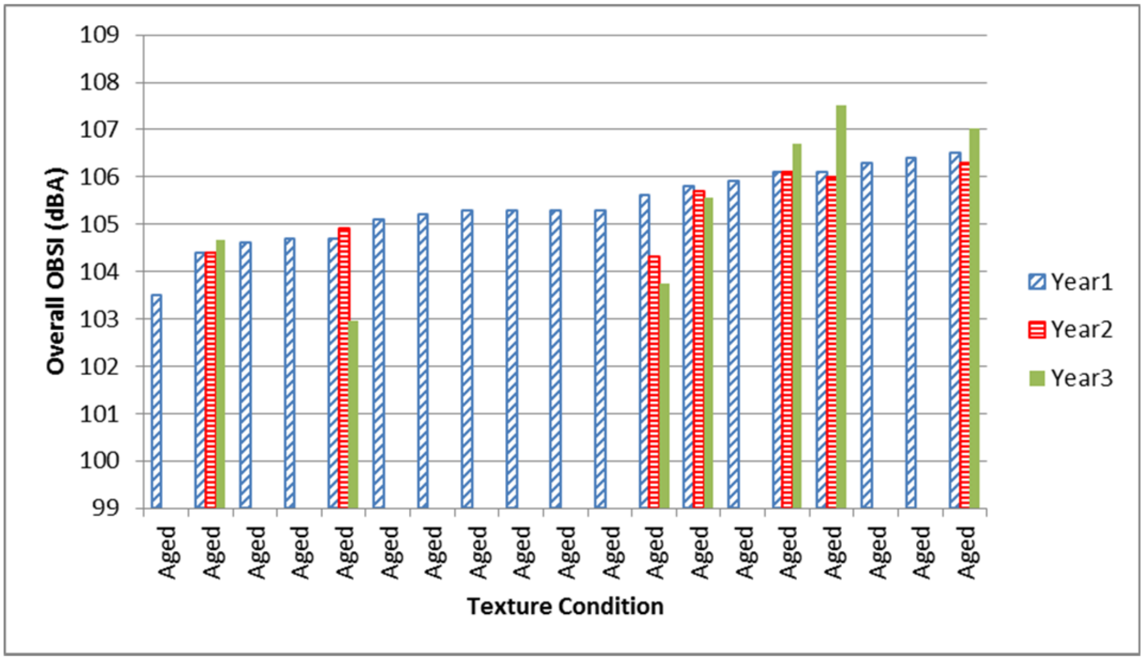


Figure C.3: Compare with Figure 3.29: Diamond-grooved Year 1, 2, and 3 OBSI results for *aged* texture sections (no *new* or *worn out* condition sections measured).

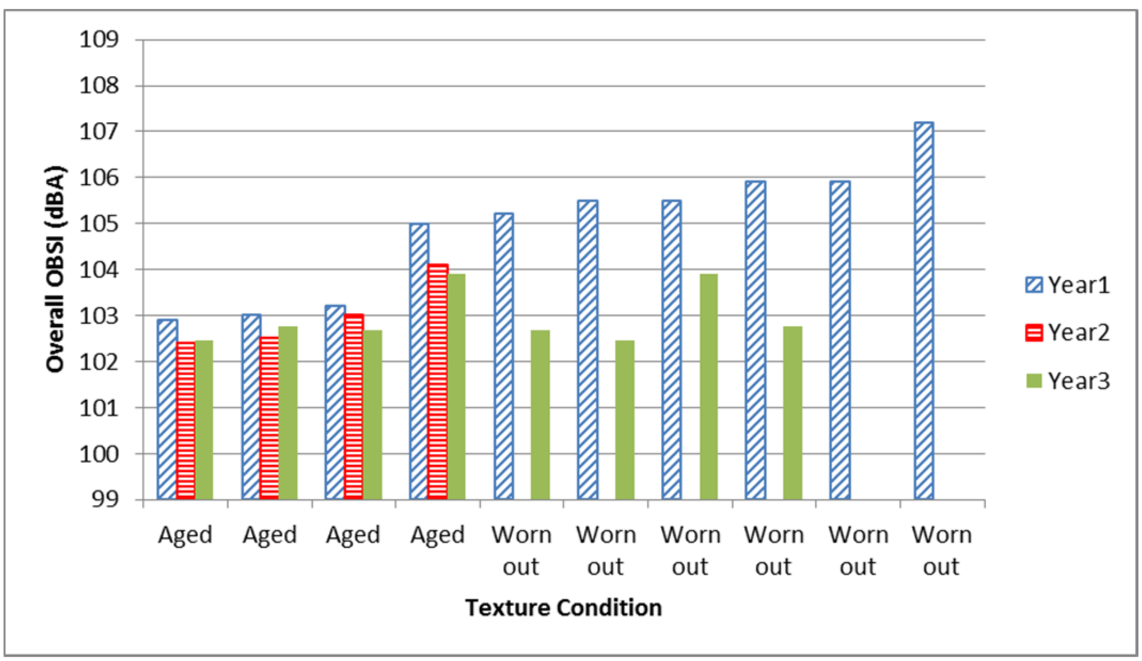


Figure C.4: Compare with Figure 3.31: Longitudinally broomed Year 1, 2 and 3 OBSI results *aged* texture sections (no *new* or *worn out* condition sections measured).

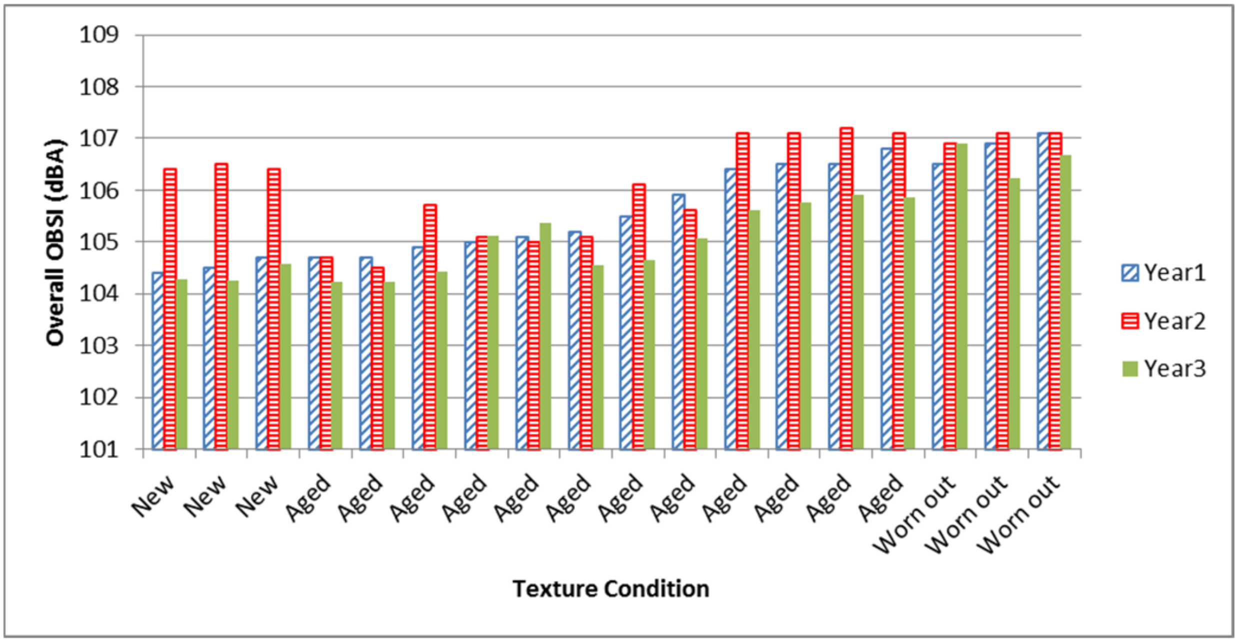


Figure C.5: Compare with Figure 3.33: Longitudinally tined Year 1, 2, and 3 OBSI results for all texture conditions *(new, aged,* and *worn out).*

APPENDIX D: SELECTED ADDITIONAL FIGURES

This appendix presents selected tables and figures from the main body of this report. Figure D.1 through Figure D.5 show the changes in OBSI noise spectra for each texture type and texture category for the three years of measurement.

Changes in OBSI Spectra Across Three Years of Measurement by Texture Type and Condition Category

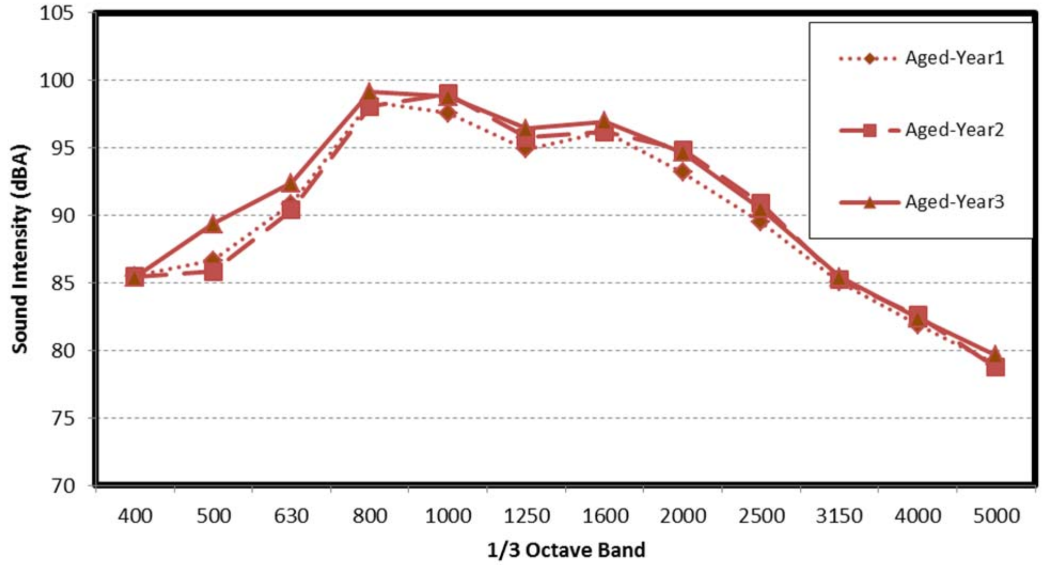


Figure D.1: Averaged OBSI spectral content of *aged* sections with burlap drag surface texture for three years of measurement.

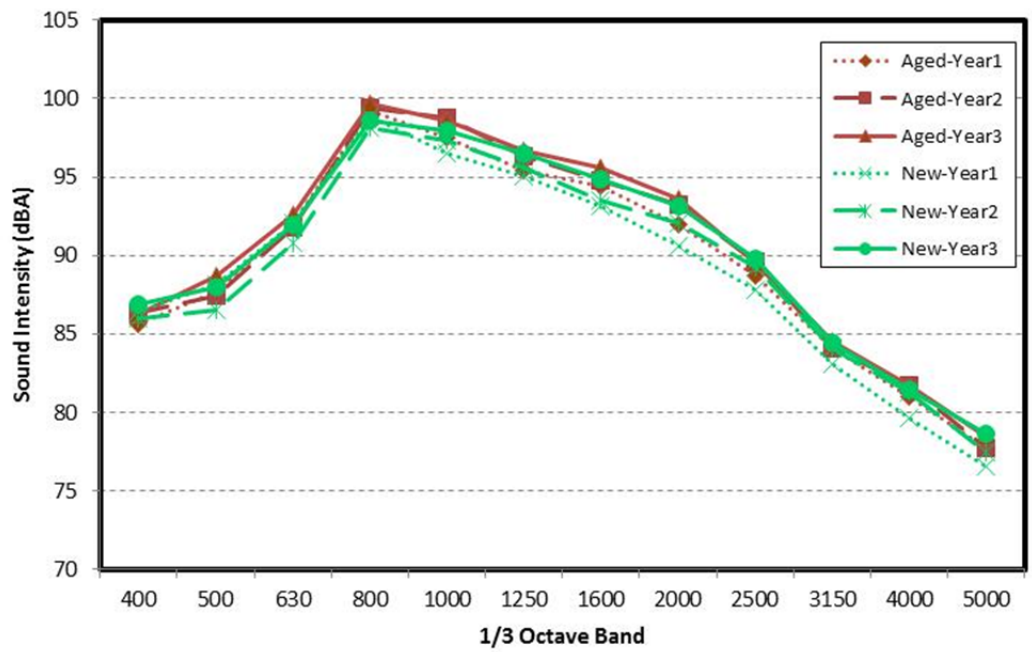


Figure D.2: Averaged OBSI spectral content of *new* and *aged* sections with diamond-ground surface texture for three years of measurement.

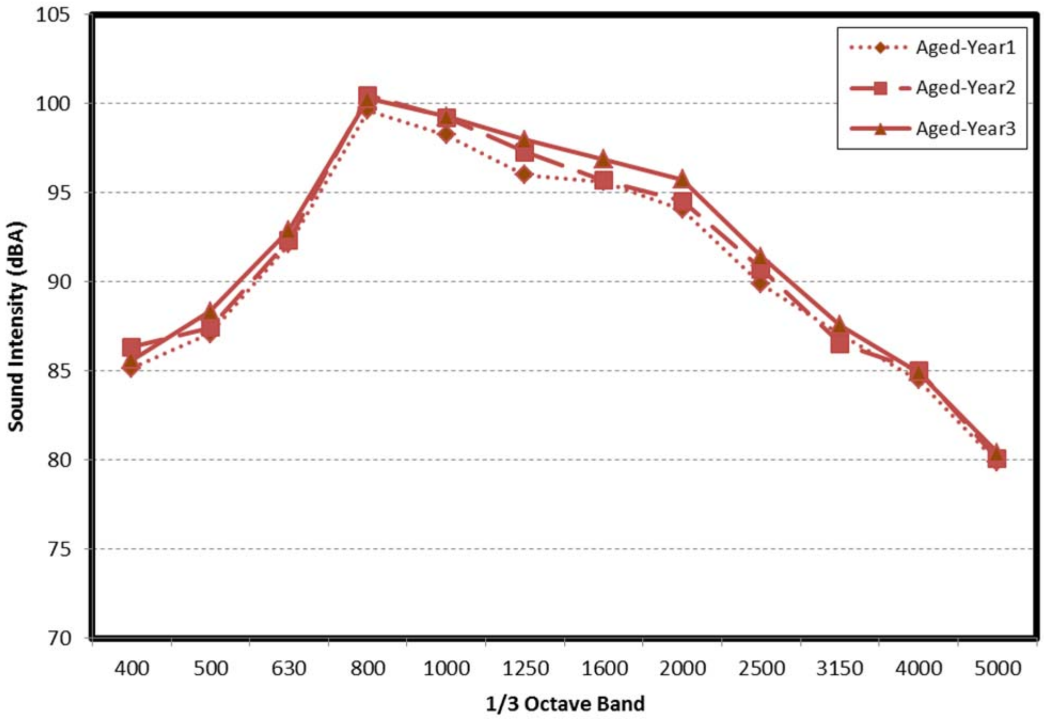


Figure D.3: Averaged OBSI spectral content of *aged* sections with diamond-grooved surface texture for three years of measurement.

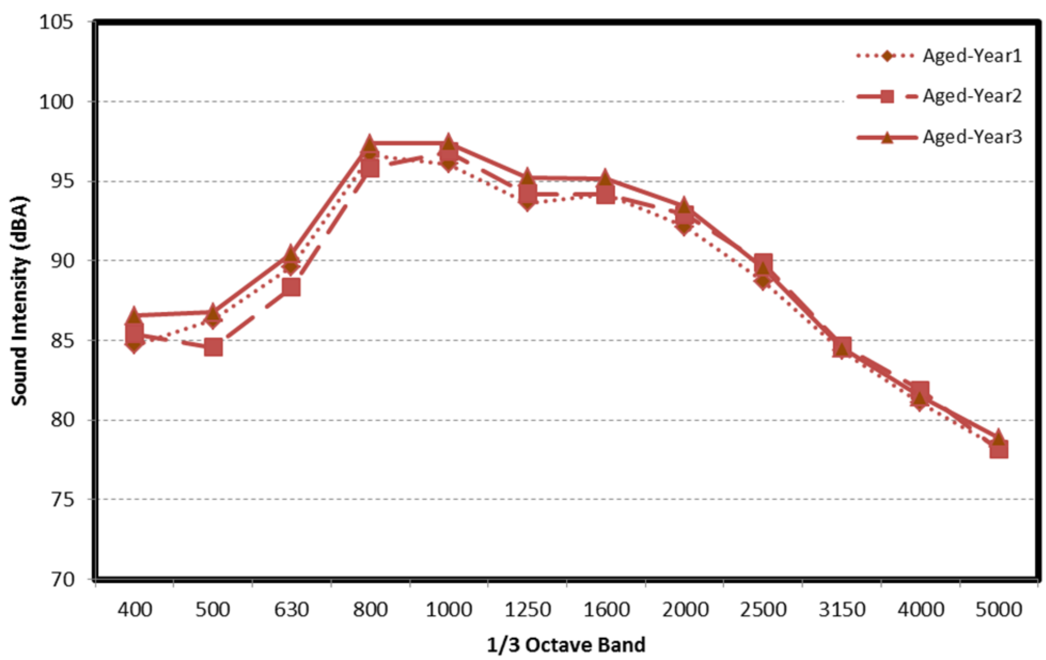


Figure D.4: Averaged OBSI spectral content of *aged* sections with longitudinally broomed surface texture for three years of measurement.

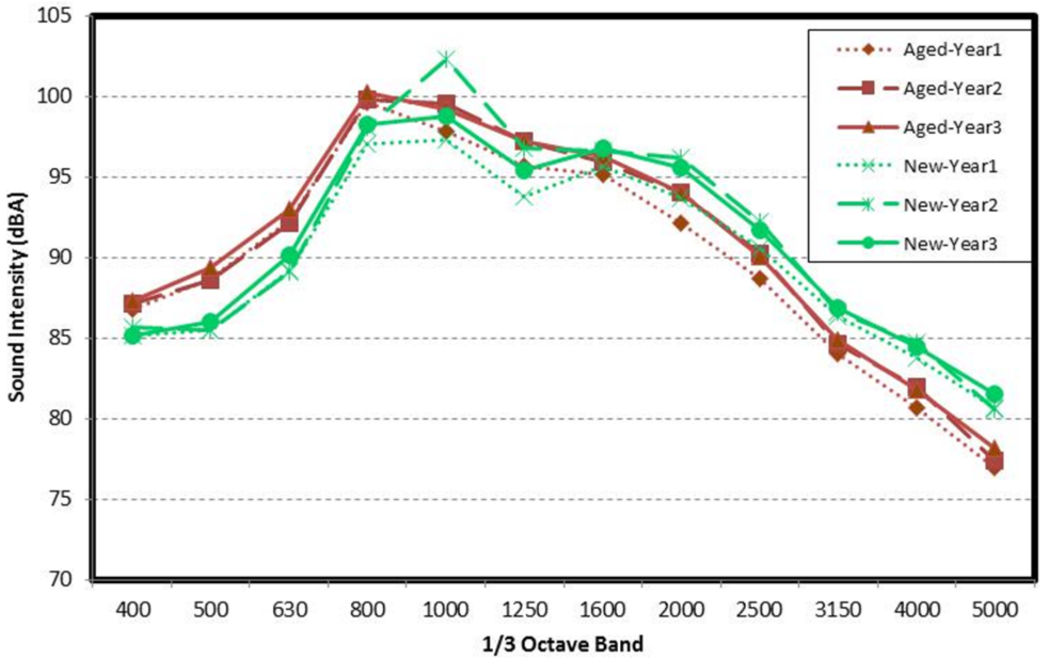


Figure D.5: Averaged OBSI spectral content of *new* and *aged* sections with longitudinally tined surface texture for three years of measurement.