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16. ABSTRACT

The work presented in this report is the culmination of a series of research projects, whose purpose is to support the Caltrans Quieter Pavement Research program. The goal of this program is to identify quieter, smoother, safer, and more durable pavement surfaces. The research has been carried out as Partnered Pavement Research Center Strategic Plan Element numbers 4.16, 4.19, 4.27, 4.29, and 4.39. This report presents six years of collected tire/pavement noise, ride quality, macrotexture, and other field data gathered on California pavements surfaced with four typical Caltrans asphalt mixes. The report also includes data from several pavement sections with experimental mixes and/or the results of side-by-side comparisons of different mixes. The experiment included pavements that ranged in age from newly paved (just after construction) to eight years old at the start of the study, resulting in data covering pavement surfaces with ages up to 15 years old. The six years of collected data were analyzed to evaluate how effective open-graded mixes are in reducing noise compared with other asphalt surface types, which included dense- and gap-graded mixes. The study also examined the ride quality performance of these mixes over time. Macrotexture, permeability, and other properties of the asphalt mixes were measured to help explain tire/pavement noise. Models for noise and ride quality that had been developed earlier, and improved with each year of additional data, appear in this report updated with data from the sixth year measurements. Conclusions about tire/pavement noise, smoothness, and durability are drawn by comparing the relative performance of dense-graded mixes against the performance of opengraded rubberized and non-rubberized mixes and rubberized gap-graded mixes. Lastly, the variables that affect tire/pavement noise are

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Investigation of Noise, Ride Quality and Macrotexture Trends for Asphalt Pavement Surfaces: Summary of Six Years of Measurements

Authors:
Arash Rezaei and John T. Harvey

Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.39:
Continued Monitoring of Selected Quieter Pavement Test Sections

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation, and System
Information
Office of Roadway Research

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Authors: A. Rezaei and J.T. Harvey

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Abstract:
The work presented in this report is the culmination of a series of research projects, whose purpose is to support the Caltrans Quieter Pavement Research program. The goal of this program is to identify quieter, smoother, safer, and more durable pavement surfaces. The research has been carried out as Partnered Pavement Research Center Strategic Plan Element numbers 4.16, 4.19, 4.27, 4.29, and 4.39.

This report presents six years of collected tire/pavement noise, ride quality, macrotexture, and other field data gathered on California pavements surfaced with four typical Caltrans asphalt mixes. The report also includes data from several pavement sections with experimental mixes and/or the results of side-by-side comparisons of different mixes. The experiment included pavements that ranged in age from newly paved (just after construction) to eight years old at the start of the study, resulting in data covering pavement surfaces with ages up to 15 years old. The six years of collected data were analyzed to evaluate how effective open-graded mixes are in reducing noise compared with other asphalt surface types, which included dense- and gap-graded mixes. The study also examined the ride quality performance of these mixes over time. Macrotexture, permeability, and other properties of the asphalt mixes were measured to help explain tire/pavement noise. Models for noise and ride quality that had been developed earlier, and improved with each year of additional data, appear in this report updated with data from the sixth year measurements. Conclusions about tire/pavement noise, smoothness, and durability are drawn by comparing the relative performance of dense-graded mixes against the performance of open-graded rubberized and non-rubberized mixes and rubberized gap-graded mixes. Lastly, the variables that affect tire/pavement noise are also examined. The results presented in this report are the final analysis and models from all six years of this program investigating noise and ride quality on Caltrans' asphalt surfaces and indicate that the mix with the longest noise-reducing performance is rubberized open-graded asphalt. Tables are presented that show expected model-based life of noise and roughness reductions compared with dense-graded asphalt.

Keywords: asphalt concrete, noise, absorption, macrotexture, open-graded, gap-graded, dense-graded, on-board sound intensity, permeability, flexible pavement

Proposals for implementation: It is recommended that the results of this study be used to update the Caltrans Quieter Pavement Guidelines and performance models in the Caltrans pavement management system (PaveM).

Related documents:

- Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results, by A. Ongel, J. Harvey, E. Kohler, Q. Lu, and B. Steven. February 2008. (UCPRC-RR-2007-03). Report prepared by UCPRC for the California Department of Transportation.
- *Summary Report*: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results, by Aybike Ongel, John T. Harvey, Erwin Kohler, Qing Lu, Bruce D. Steven and Carl L. Monismith. August 2008. (UCPRC-SR-2008-01). Report prepared by UCPRC for the California Department of Transportation.
- Acoustical Absorption of Open-Graded, Gap-Graded, and Dense-Graded Asphalt Pavements, by A. Ongel and E. Kohler. July 2007. (UCPRC-TM-2007-13) Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- State of the Practice in 2006 for Open-Graded Asphalt Mix Design, by A. Ongel, J. Harvey, and E. Kohler. December 2007. (UCPRC-TM-2008-07) Report prepared by UCPRC for the California Department of Transportation.
- Temperature Influence on Road Traffic Noise: Californian OBSI Measurement Study, by H. Bendtsen, Q. Lu, and E. Kohler. May 2010. (UCPRC-RP-2010-02) Report prepared by the Danish Road Institute, Road Directorate and University of California Pavement Research Center for the California Department of Transportation.
- Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results, by Q. Lu, E. Kohler, J. Harvey, and A. Ongel. January 2009. (UCPRC-RR-2009-01). Report prepared by UCPRC for the California Department of Transportation.
- Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Four-Year Results, by Q. Lu, J. Harvey, and R. Wu. April 2011. (UCPRC-RR-2010-05). Report prepared by UCPRC for the California Department of Transportation.
- Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Five-Year Results, by A. Rezaei, J. Harvey, and Q. Lu. April 2011. (UCPRC-RR-2012-04). Report prepared by UCPRC for the California Department of Transportation.

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DISCLAIMER

PROJECT OBJECTIVES

The research presented in this report is part of the California Department of Transportation (Caltrans) Quieter Pavement Research (QPR) Work Plan, whose purpose is to support the Caltrans Quieter Pavement Research program. The QPR program has the goal of identifying quieter, smoother, safer, and more durable pavement surfaces.

The goal of the project presented in this report, which is part of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.39, is to complete the acoustical and ride quality performance testing and modeling for the factorial of asphalt pavements that has been tested in previous years. PPRC SPE 4.39 goals for concrete pavements and other goals have been completed with additional projects and reports.

PPRC SPE 4.39 has the following objectives for asphalt-surfaced pavements:

1. Perform a sixth and final year of data collection for tire/pavement noise, ride quality, macrotexture, and permeability on the remaining in-service asphalt-surfaced pavement test sections from the original factorial experiment.
2. Collect data on sections that have experimental asphalt surface types or that were set up as side-by-side comparisons of tire/pavement noise performance of different mixes.
3. Determine the rates of change for the noise and ride quality of asphalt-surfaced sections by adding the new data to the data from the previous five years of performance measurement and updating the earlier models developed.
4. Report on the updated models and data, summarize the trends for noise (OBSI) and smoothness (IRI), and develop predictions for pavement life for these variables.

This report documents the work completed to accomplish these objectives.

EXECUTIVE SUMMARY

The California Department of Transportation (Caltrans) employs a variety of strategies and materials in maintaining and rehabilitating the state highway system's pavements, a necessary approach given the varying characteristics of the pavements in use and their diverse properties. Key pavement characteristics among the many that Caltrans must manage are *pavement smoothness*, which affects road user costs, road user comfort, and vehicle emissions, and *quietness*, which affects the quality of life of people who use highways and those who live near them. In order to determine the most cost-effective approaches for maintaining roadway smoothness and quietness, Caltrans is seeking to identify the longevity of current materials and strategies, as well as those of potential alternatives. To accomplish this, Caltrans established the Quieter Pavement Research (QPR) Program.

The Caltrans QPR program is intended to examine the impact of quieter pavements on traffic noise levels and to establish which pavement surface characteristics have the greatest impact on tire/pavement noise. The program also aims to identify surface treatments, materials, and construction methods that will result in quieter pavements that are also safe, durable, and cost-effective. The information gathered as part of the program will be used to develop quieter pavement policies, design features, and specifications for noise abatement throughout the state.

The QPR program includes several studies to evaluate the acoustic properties of pavements and the role that pavement surface characteristics play relative to tire/pavement noise levels. The Caltrans QPR Work Plan includes research on both asphalt (also referred to as "flexible") and concrete (also referred to as "rigid") pavement surfaces. For the asphalt surface pavement part of the QPR program, Caltrans previously identified a need for research into the acoustics, friction, and distress performance of asphalt pavement surfaces, and as a response it initiated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 in November 2004. Among its other objectives, PPRC SPE 4.16 developed preliminary performance estimates for current Caltrans asphalt surfaces—including what at the time were called dense-graded asphalt concrete (DGAC), open-graded asphalt concrete (OGAC), rubberized asphalt concrete gap-graded (RAC-G), and rubberized asphalt concrete open-graded (RAC-O) as part of a factorial experiment—and for a number of experimental asphalt surfaces with respect to tire/pavement noise, permeability, macrotexture, microtexture, smoothness, and surface distress development.[1]

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[1] The technical names for these mixes have changed in Section 39 of the Caltrans Standard Specifications. In this report, the names in use at the start of PPRC SPE 4.16 have been maintained in order to retain consistency among all the reports and technical memoranda generated by the quieter pavement studies. Current names for these materials are hot-mix asphalt (HMA), open-graded asphalt concrete (OGAC, which is unchanged from the earlier naming system), rubberized hot-mix asphalt gap-graded (RHMA-G), and rubberized hot-mix asphalt open-graded (RHMA-O).

PPRC SPE 4.16 included two years of field measurement of the tire/pavement noise and other surface properties of asphalt pavements, beginning in January 2006, laboratory testing of field cores, modeling, and performance predictions (see References 1 and 2 in the body of the report). PPRC SPE 4.19 was initiated in September 2007 and it updated the earlier performance estimates using a third year of measurements taken on most of the pavement sections included in PPRC SPE 4.16 (*3*). The QPR study continued with a fourth phase that included measurements taken in 2008 and 2009 under PPRC SPE 4.27 (*4*) and with a fifth phase of measurements under SPE 4.29 in 2009/2010 (*5*). This current report summarizes the results from the sixth year of the study, which combines data from all six years of measurements. It is the culmination of the studies on asphalt surfaces.

Project Goal and Objectives

The goal of the project presented in this report, which is part of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.39, is to complete the acoustical and ride quality performance testing and modeling for the factorial of asphalt pavements that has been tested in previous years. PPRC SPE 4.39 goals for concrete pavements and other goals have been completed with additional projects and reports.

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3 Determine the rates of change for the noise and ride quality of asphalt-surfaced sections by adding the new data to the data from the previous five years of performance measurement and updating the earlier models developed.

4 Report on the updated models and data, summarize the trends for noise (OBSI) and smoothness (IRI), and develop predictions for pavement life for these variables.

This report documents the work completed to accomplish these objectives.

Scope of the Report

Chapters 2 through 5 of this report present results for the current Caltrans asphalt surfaces: DGAC, OGAC, RAC-G, and RAC-O. Chapter 2 presents results for the International Roughness Index (IRI). Chapter 3 presents results for Mean Profile Depth (MPD), which is a measure of surface macrotexture related to high-speed skid resistance and which also affects tire/pavement noise. Chapter 4 presents results for On-board Sound Intensity

(OBSI) measurements of tire/pavement noise. Chapter 5 presents an update of performance measurements on the experimental test sections referred to as “Environmental Sections” (ES). The statistical models developed from six years of data used to estimate the life of the each surface type (RAC-G, RAC-O, OGAC, DGAC) appear in Chapter 6. Chapter 7 presents a summary, conclusions, and recommendations. The details of data presentation, analysis, and modeling are given in the appendices.

Results

A summary of the test sections included in the six years of testing is presented in the report, as are data plots, summary statistics, and discussions of the trends for each of the variables included in all six years of data collection: macrotexture, ride quality and tire/pavement noise. Data collected on the Environmental Sections is plotted and the trends observed are reviewed in Chapter 5. The data collected over six years was used to develop statistical models, which were in turn used to predict the functional life of the four surface mix types. These predictions can be used to update policies, and the information can also be used in the pavement management system.

The sixth-year data featured in this report will be included in a relational database that will be delivered to Caltrans separately. Specific data in the database include:

- Microtexture data collected for the first two years and macrotexture data for all six years, both of which affect skid resistance
- Ride quality data in terms of International Roughness Index (IRI) for all six years
- On-board Sound Intensity (OBSI) data, a measure of tire/pavement noise, for all six years
- Sound intensity data for different frequencies for all six years
- Climate data
- Traffic data

The analyses presented for each performance variable in Appendices A.2 through A.5 include a summary of descriptive statistics and, where the data is sufficient, statistical models. The appendices also provide a summary of the development of calibration equations for OBSI and detailed condition survey information.

Conclusions

Performance of Open-Graded Mixes

For newly paved DGAC overlays, the average tire/pavement noise level was approximately 101.3 dBA. The study results showed that average tire/pavement noise levels for newly paved overlays with OGAC, RAC-G, and RAC-O open-graded mixes were lower than those of the DGAC mixes by median values of approximately 0.1 dBA, 1.0 dBA, and 1.9 dBA, respectively.

After the pavements were exposed to traffic, the OGAC noise benefit generally diminished slightly for about six to seven years. The noise-reduction benefit lasted longer for RAC-O than for OGAC, and RAC-O remained quieter than DGAC of the same age for between 10 and 11 years. However, after nine years, none of the RAC-O sections remained quieter than DGAC sections of the same age by more than 3 dBA. This is important because 3 dBA has been identified as the threshold value at which most humans can perceive a difference in noise. For this reason, highway noise changes of less than 3 dBA are generally considered to be relatively insignificant (9). It should be noted though that that threshold is based on studies of humans listening to pure tones in a laboratory setting, such as in a common hearing test. Also, many people can hear less than 3 dBA differences in tire/pavement noise and/or perceive differences in the frequency content of two tire/pavement noise sources that have the same sound intensity (as measured in dBA).

The main advantage gained from use of open-graded mixes comes from their ability to reduce high frequency noise because they have high permeability which reduces the air-pumping tire/pavement noise mechanism, and the newly paved open-graded OGAC and RAC-O overlays generally had lower high-frequency noise than the less permeable dense-graded mixes. Macrotexture as measured by MPD, which when it is positive (stones protruding up from surface) has a large influence on low frequency noise through tire vibration, was lower for newly constructed RAC-G and DGAC mixes than for open-graded mixes. Low-frequency noise increased with age, likely due to the increase in surface distresses, primarily raveling as measured by MPD. Increases in low frequency noise contribute to overall noise levels, and the benefits of reduced high frequency noise for open-graded mixes can be offset by increases in low frequency noise. Measured data indicate that OGAC pavements are more prone to development of raveling than RAC-O mixes after six to eight years of trafficking.

The surface types OGAC, RAC-G, and RAC-O all had lower IRI than DGAC over the full data set, but only OGAC and RAC-O were statistically significantly different from DGAC. Monitoring over six years indicates that IRI increases with age on all mix types, but that age had a statistically significant effect in increasing IRI on DGAC and RAC-O at a 5 percent significance level but not on OGAC and RAC-G.

Performance of RAC-G Mixes

The newly paved RAC-G mixes were quieter than an average newly paved DGAC mix by about 1.8 dBA *(1)*. However, the tire/pavement noise on RAC-G mixes approached the average noise level of DGAC pavements of similar ages within three to five years after construction. The main change in noise level occurred at high frequencies. Moreover, the RAC-G mixes had higher low-frequency noise and lower high-frequency noise than DGAC mixes. In the first three years after the pavements were exposed to traffic, high frequency noise increased considerably with age, due to the reduction of surface permeability and air-void content under traffic, while low-frequency noise (equal to or less than 1,000 Hz) was nearly unchanged with age. In sections with severe raveling, the low frequency noise increase quickly and degraded the noise-reduction benefit of the RAC-G pavements.

The IRI values on newly paved RAC-G mixes were somewhat lower than those measured on DGAC mixes. The rate of increase in IRI on newly paved for RAC-G mixes was smaller than on similarly aged DGAC mixes.

The MPD values on newly paved RAC-G mixes were higher than on DGAC mixes. The rate of increase in MPD on old RAC-G was higher than that on similarly aged DGAC.

Performance of Environmental Sections

During the noise study of environmental sections, the noise, ride quality, and surface macrotexture of twenty-one environmental sections were measured, eight of which had continued monitoring in the sixth year. The following conclusions were drawn from the results of this study:

Results obtained from the Fresno 33 sections showed that the RAC-G and Type G-MB mixes generally exhibited the highest and lowest MPD values, respectively. The RAC-G and RUMAC-GG mixes exhibited higher IRI values than the Type G-MB, Type D-MB, and DGAC mixes. No indication could be seen of the effect of layer thickness on the measured IRI and MPD of any of these mixes. The Type G-MB 45 mm thick overlays exhibited the lowest sound intensity, with a value of 102.7 dBA. None of these mixes provided any noise reduction benefit compared to the DGAC mixes after seven years in service.

Of the two sections with thin RAC-O overlays on concrete pavement, the San Mateo 280 section (10 years old at final measurement) performed better than the Sacramento 5 sections (seven years old) in terms of both noise and roughness, possibly due to the San Mateo section’s greater layer thickness and lower truck traffic. The RAC-O pavement placed on the Sacramento 5 northbound exhibited a major increase in IRI.

Results from the LA 138 test sections, which includes sections with the DGAC, OGAC, RAC-O, and BWC mix types, showed that RAC-O mixes had the lowest IRI values noise levels of all these mixes. After the sixth year of measurement, when they were 10 years old, the OGAC mixes showed no significant difference in noise compared with the DGAC mixes. Further, there seemed to be no interaction between surface layer thickness and overall sound intensity after six years.

Results on the LA 19 EU-GG mix up through five years, after which measurements were stopped, showed that it performed well in terms of providing sound-reduction benefits, compared with statewide data collected for DGAC. Although this mix also showed a year-to-year increase in IRI, it was not significant.

The Yolo 80 section is still providing good ride quality according to FHWA guidelines, but it has lost its noise-reducing capabilities, as shown by a comparison with statewide data for DGAC. At its current age of 13 years, the section's overall sound intensity is slightly more than 105 dBA. The noise spectrum of this section indicates that the increase of noise mainly occurred at frequencies lower than 1,000 Hz, an indication of raveling.

Almost all the BWC sections included in this study provided good ride quality. The BWC mixes appeared to provide an immediate noise reduction benefit, and then appeared to lose it by the time of the last measurements when they were five to seven years old. At that time, no noise-reduction benefit from use of BWC was observed compared with new DGAC.

Variables Affecting Tire/Pavement Noise

The findings from this sixth year of the study regarding the variables that affect tire/pavement noise are generally in agreement with the significant factors found in the earlier reports *(2, 3, 4, 5)*. Tire/pavement noise is greatly influenced by surface mix type and mix properties, age, traffic volume, and the presence of distresses. Noise levels generally increased primarily with traffic volume and pavement age. Overall noise levels decreased with increased surface layer thickness and permeability (or air-void content) for open-graded mixes.

For all the mix types (DGAC, RAC-G, OGAC, and RAC-O), the aggregate gradation variable (fineness modulus) had an effect on some noise frequencies; however, neither the nominal maximum aggregate size (NMAS) or the gradation significantly affected overall tire/pavement noise within each mix type. It should be noted that this conclusion is based on an analysis of mixes with a limited number of aggregate gradation distributions. Further investigation is required to draw more conclusive results.

Pavement surface macrotexture (MPD) was a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponded to a higher noise level, particularly at lower frequencies. For OGAC and RAC-O pavements, MPD did not have a significant influence on noise level.

Recommendations

It is recommended that the predictions for noise and IRI developed as part of this study be used along with other Caltrans criteria to determine where the use of quieter pavement is cost-effective. It is recommended that where quieter asphalt pavement is used instead of DGAC as the surface material, that RAC-O be used since it provides better performance with respect to noise and IRI than OGAC or RAC-G.

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
in. Ft	inches feet	25.4 0.305	millimeters meters	mm m
AREA				
in.^{2} ft^2	square inches square feet	645.2 0.093	square millimeters square meters	mm^2 m^2
VOLUME				
ft^3	cubic feet	0.028	cubic meters	m^3
MASS				
lb	pounds	0.454	kilograms	kg
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	C
FORCE and PRESSURE or STRESS				
lbf lbf/in.^{2}	poundforce poundforce/square inch	4.45 6.89	newtons kilopascals	N kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm m	millimeters meters	0.039 3.28	inches feet	in. ft
AREA				
mm^2 m^2	square millimeters square meters	0.0016 10.764	square inches square feet	in.^{2} ft^2
VOLUME				
m^3	cubic meters	35.314	cubic feet	ft^3
MASS				
kg	kilograms	2.202	pounds	lb
TEMPERATURE (exact degrees)				
C	Celsius	1.8C+32	Fahrenheit	F
FORCE and PRESSURE or STRESS				
N kPa	newtons kilopascals	0.225 0.145	poundforce poundforce/square inch	lbf lbf/in.^{2}

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (revised March 2003).

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1 INTRODUCTION

1.1 Project Background

The California Department of Transportation (Caltrans) employs a variety of strategies and materials in maintaining and rehabilitating the state highway system's pavements, a necessary approach given the varying characteristics of the pavements in use and their diverse properties. Key pavement characteristics among the many that Caltrans must manage are *pavement smoothness,* which affects road user costs, road user comfort, and vehicle emissions, and *quietness*, which affects the quality of life of people who use highways and those who live near them. In order to determine the most cost-effective approaches for maintaining roadway smoothness and quietness, Caltrans is seeking to identify the longevity of current materials and strategies, as well as those of potential new alternatives. To accomplish this identification, Caltrans established the Quieter Pavement Research (QPR) Program.

The program's purpose is to examine what effects quieter pavements have on traffic noise levels and to determine which pavement surface characteristics have the greatest impact on tire/pavement noise. The program also aims to identify surface treatments, materials, and construction methods that will result in quieter pavements that are also safe, durable, and cost-effective. The information gathered as part of the program will be used to develop quieter pavement policies, design features, and specifications for noise abatement throughout the state.

The QPR program has included several studies evaluating the acoustic properties of pavements and the role pavement surface characteristics play relative to tire/pavement noise levels. The Caltrans QPR Work Plan includes research on both asphalt and concrete pavement surfaces. For the asphalt surface pavement part of the QPR program, Caltrans previously identified a need for research into the acoustics, friction, and distress performance of asphalt pavement surfaces, and as a response it initiated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 in November 2004. Among its other objectives, PPRC SPE 4.16 developed preliminary performance estimates for current Caltrans asphalt surfaces—including what at the time were called dense-graded asphalt concrete (DGAC), open-graded asphalt concrete (OGAC), rubberized asphalt concrete gap-graded (RAC-G), and rubberized asphalt concrete open-graded (RAC-O) as part of a factorial experiment—and for a number of experimental asphalt surfaces with respect to tire/pavement noise, permeability, macrotexture, microtexture, smoothness, and surface distress development.[2]

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[2] The technical names for these mixes have changed in Section 39 of the Caltrans Standard Specifications. In this report, the names in use at the start of PPRC SPE 4.16 have been maintained in order to retain consistency among all the reports and technical memoranda generated by the quieter pavement studies. Current names for these materials are hot-mix asphalt (HMA), open-graded asphalt concrete (OGAC, which is unchanged from the earlier naming system), rubberized hot- mix asphalt gap-graded (RHMA-G) and rubberized hot- mix asphalt open-graded (RHMA-O).

PPRC SPE 4.16 included two years of field measurement of the tire/pavement noise and other surface properties of asphalt pavements, beginning in January 2006, laboratory testing of field cores, modeling, and performance predictions *(1,2)*. PPRC SPE 4.19 was initiated in September 2007 and updated performance estimates from a third year of measurements on most of the pavement sections included in the PPRC SPE 4.16 *(3)*. The QPR study was further continued with measurements taken in 2008 and 2009 under PPRC SPE 4.27 (*4*) and a fifth year under SPE 4.29 in 2009/2010 (*5*). This current report summarizes the results from the sixth-year study, combining the data from all six years of measurements, and is the culmination of the studies on asphalt surfaces.

Figure 1.1 shows a timeline of the data collection periods for the noise and field properties testing for both the asphalt and concrete noise studies.

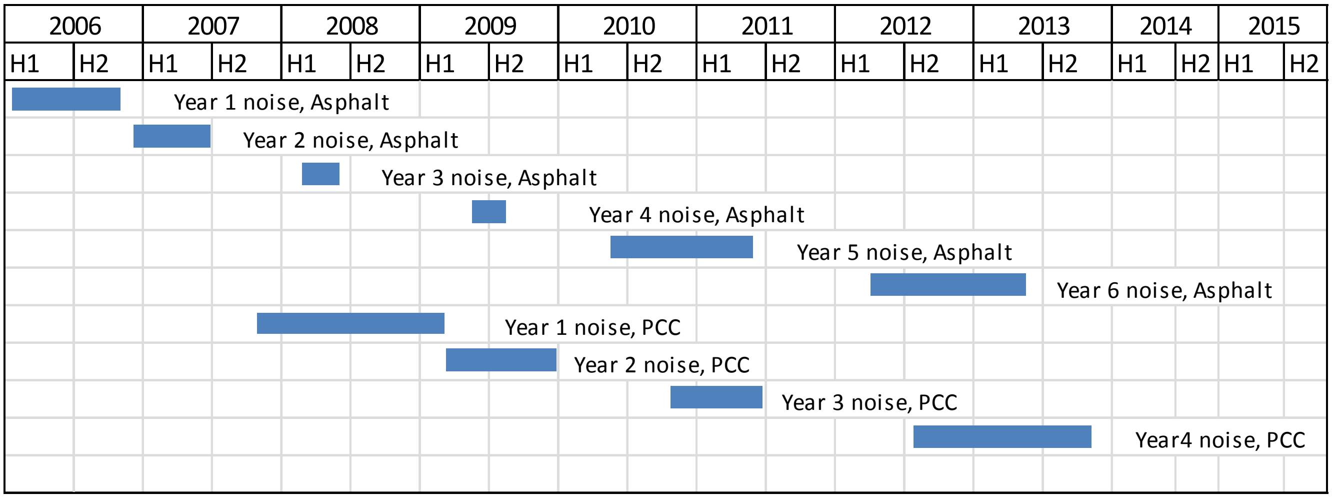

Figure 1.1: Timeline of completed data collection periods for asphalt and concrete pavement noise studies.

1.2 Project Goal and Objectives

The goal of the project presented in this report, which is part of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.39, is to complete the acoustical and ride quality performance testing and modeling for the factorial of asphalt pavements that has been tested in previous years. PPRC SPE 4.39 goals for concrete pavements and other goals have been completed with additional projects and reports.

PPRC SPE 4.39 has the following objectives for asphalt-surfaced pavements:

1. Perform a sixth and final year of data collection for tire/pavement noise, ride quality, macrotexture, and permeability on the remaining in-service asphalt-surfaced pavement test sections from the original factorial experiment.

2. Collect data on sections that have experimental asphalt surface types or that were set up as side-by-side comparisons of tire/pavement noise performance of different mixes.
3. Determine the rates of change for the noise and ride quality of asphalt-surfaced sections by adding the new data to the data from the previous five years of performance measurement and updating the earlier models developed.
4. Report on the updated models and data, summarize the trends for noise (OBSI) and smoothness (IRI), and develop predictions for pavement life for these variables.

This report documents the work completed to accomplish these objectives.

1.3 Experiment Factorial and Test Methods for Sixth-Year Measurement

As noted earlier, a factorial was developed as part of PPRC SPE 4.16 for current Caltrans asphalt surfaces including DGAC, RAC-G, OGAC, and RAC-O.[3] The Year 1 factorial included 60 sections, referred to as the *Quieter Pavement* (QP) sections, which were selected based on surface mix type (DGAC, RAC-G, OGAC, RAC-O), climate region (rainfall), traffic (Average Daily Truck Traffic [ADTT]), and years since construction at the time of the initial measurement. This last parameter was referred to as *Age Category* and was grouped at the time of the first year of measurements into three ranges: less than one year, one to four years, or four to eight years. In addition, 23 sections were constructed to provide side-by-side comparisons of different surface mixes, to try new mixes, or to continue previous noise measurements begun by Caltrans; these sections, which were referred to as the *Environmental Sections* (ES) because most of them were identified by the Division of Environmental Analysis, were also tested. Various sections in both the QP and ES experiments were dropped from year to year because they were overlaid or, in a few cases, because of safety concerns. Table 1.1 shows the number of sections surveyed for various performance measures in each of the six years. Table B.1 and Table B.2 in Appendix B.1 show detail of the sections included in each year of testing. For the third year of data collection, fifteen of the ES sections were dropped and seven new sections with a new surface mix type called Bituminous Wearing Course (BWC) were added to the experimental design.

In each year of the experiment, the UCPRC instrumented vehicle collected data on noise, ride quality, and macrotexture on all sections at highway speeds. Over the course of the study, the following additional data were collected:

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[3] See Footnote 2 on page 22 regarding terminology for pavement types used in this report.

- Condition survey data on surface distresses observed from the shoulder of the road: Years 1, 2, 3 and 4
- Permeability test data from within traffic closures: Years 1, 2, and 4 (31 sections) and Year 6 (10 sections)
- Friction (microtexture) data from testing performed within traffic closures: Years 1 and 2
- Mix property data from laboratory testing on cores taken in traffic closures: Years 1, 2, and 4 (31 sections) and Year 6 (10 sections).

Detailed descriptions of project testing methodologies, definitions, and background appear in Reference *(2),* and most of the same data collection methodologies were continued throughout this study. One exception, however, was the test tires used in the study. For most of its first two years, the study used Aquatred tires for noise measurement, but after the end of the second year, those tires were replaced with Standard Reference Test Tires (SRTT). This required conversion of all the measurements from the first two years of testing to equivalent noise levels measured with one specific SRTT tire (SRTT#1). To do this, UCPRC developed correction equations at the end of the second year of measurement. From the third year on, a new SRTT tire was used for each year of measurement, and a correction equation to the reference SRTT tire was developed for each new tire. Development of the correction equations is documented in the report for each year of the study (*2-5*) and is summarized for the first four years of testing in Reference (*6*).

Air density adjustments were applied to all the data from all six years using correction equations that are documented in Reference *(2)*.

A Larson Davis noise data analyzer used in the first three years of data collection was changed to a Harmonie unit in the fourth year, introducing small changes in certain frequencies. The data analyzer change was made because the Larson Davis equipment lacked the capability to simultaneously trigger all data collection channels, a capability that the Harmonie analyzer has. Correction equations were then developed and applied to the earlier data, converting all those measurements to the equivalents of measurements made by the Harmonie analyzer used for the remaining years of the study.

A new test vehicle was used beginning in the fifth year of noise, ride quality, and texture measurement. Unlike the situations with the tire and noise data analyzers, though, comparisons of back-to-back measurements using the two vehicles and different tires showed that no correction was needed.

Details of the correction equations used to convert data to equivalent values for the Harmonie analyzer and SRTT#1 are shown in Appendix B.2.

Table 1.1: Number of Sections with Valid Measurements in Six Years

	Year 1 (Phase 1, 2006)	Year 2 (Phase 2, 2006-07)	Year 3 (Phase 3, 2008)	Year 4 (Phase 4, 2009)	Year 5 (Phase 5, 2010-11)	Year 6 (Phase 6, 2011-13)
Tire/Pavement Noise (OBSI-California)*	76	71	65	62	65	32
Roughness (ASTM E1926)	78	71	69	67	65	32
Macrotexture (ASTM E1845)	77	72	60	67	65	32
Friction (ASTM E303)	83	73	0	0	0	0
Air-void Content/Aggregate Gradation**	83/83	73/73	0/0	27/0	0	10
Permeability (NCAT falling head)	78	73	0	31	0	10
Pavement distresses**	84	84	73	72	0	10

Notes:

* ASTM and AASHTO test methods currently being standardized based in part on California experience (ASTM WK26025 - New Practice for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity [OBSI] Method; AASHTO TP 76 EN-Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity [OBSI] Method).

** See Reference *(2)* for method description.

1.4 Scope of this Report

Chapters 2 through 5 of this report present results for the current Caltrans asphalt surfaces: DGAC, OGAC, RAC-G, and RAC-O. Chapter 2 presents results for the International Roughness Index (IRI). Chapter 3 presents results for Mean Profile Depth (MPD), which is a measure of surface macrotexture related to high-speed skid resistance and which also affects tire/pavement noise. Chapter 4 presents results for On-board Sound Intensity (OBSI) measurements of tire/pavement noise. Chapter 5 presents an update of performance measurements on the experimental test sections referred to as “Environmental Sections” (ES). The statistical models developed from six years of data used to estimate the life of the each surface type (RAC-G, RAC-O, OGAC, DGAC) appear in Chapter 6. Chapter 7 presents a summary, conclusions, and recommendations. The details of data presentation, analysis, and modeling are given in the appendices.

2 SURFACE PROFILE RESULTS: IRI

International Roughness Index (IRI) data was collected in all six years of the study so that changes in the surface roughness of asphalt pavements could be evaluated. The IRI measurements were collected in both the left and right wheelpaths. The analysis used the average of the two wheelpath measurements, referred to as the *mean roughness index* (MRI), along the entire length of each test section.

Figure 2.1 shows the average IRI measured over six consecutive years for each individual pavement section in both the factorial experiment (Quieter Pavement, QP) and among the Environmental Sections (ES), subdivided into each of the four mix types—DGAC, OGAC, RAC-G, and RAC-O. In each of the plots in Figure 2.1, the first data point corresponds to the section's age when the first measurement was taken, with Year Zero defined as the year the section was constructed. The y-axis of each plot shows IRI in metric units (m/km), and a caption note includes the metric equivalent needed to convert the data to U.S. standard units (in./mi). Metric units were used in the study when it was initiated and for consistency all the subsequent data was recorded using those same units.

It should be noted that neither the IRI values at the time of overlay construction nor soon thereafter are known, except for those sections tested soon after construction. The original condition of the pavement layers beneath the overlays is also unknown.

Almost all the sections exhibited a trend of increasing IRI, indicating that the road surface became rougher over time. A major decrease in IRI for QP-26 (RAC-G) might have been due either to difficulties in measurement (such as problems retracing the earlier wheelpath) or to road maintenance. This section was treated as an outlier and was removed from the subsequent analysis. QP-16 had the highest IRI values, probably due to severe raveling.

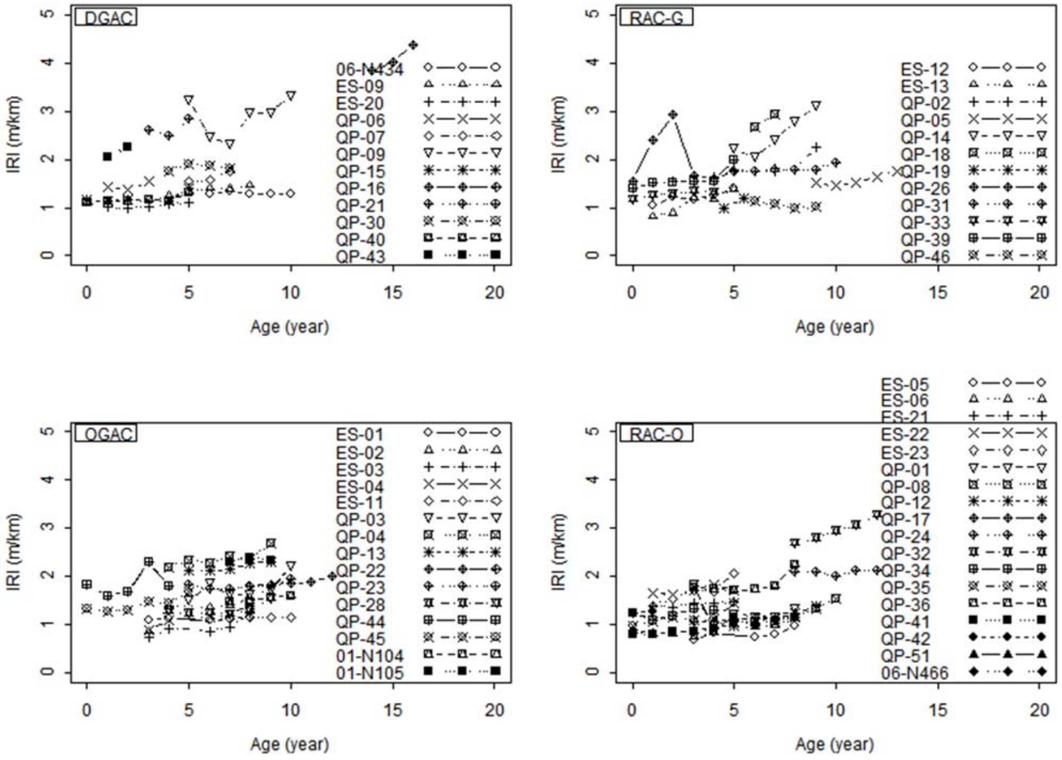

Figure 2.1: IRI trends over six years for each pavement section.
(*Note:* 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi.)

Details of both descriptive and statistical analyses are presented in Appendix A.2. The following findings were obtained regarding roughness:

1. The IRI models for DGAC and RAC-G have R^2 above 0.65, while the OGAC and RAC-O models have R^2 of about 0.4. This indicates that the roughness performance of the open-graded mixes was not explained well by the variables included in this study. Part of this may be due to differences in initial construction smoothness, which was not controlled in terms of IRI as part of the construction quality assurance process.
2. Except for one DGAC section, throughout the study all sections were smoother than the old Caltrans Pavement Management System (PMS) IRI trigger criterion of 3.6 m/km (224 in./mi). After the six years of the study, less than about 35 percent of the observations made on the DGAC test sections that were more than four years old at the start of the study showed IRI levels higher than the current PMS IRI trigger of 2.7 m/km (170 in./mi), and less than about 20 percent of the other mix types of similar age at the beginning of the study reached that level of roughness. This indicates that Caltrans generally treats pavements before they reach that IRI trigger.

3. Rubberized open-graded mixes had lower initial IRI values than non-rubberized open-graded mixes; non-rubberized dense-graded mixes had lower initial IRI values than rubberized gap-graded mixes.
4. The surface types OGAC, RAC-G, and RAC-O all had lower IRI than DGAC over the full data set, but only OGAC and RAC-O were statistically significantly different from DGAC. Monitoring over six years indicates that IRI increases with age on all mix types, but that the statistical significance of age varies. Specifically, age is statistically significant at a 5 percent level in increasing IRI on DGAC and RAC-O, but it was not significant on a level that high on OGAC and RAC-G.
5. Open-graded pavements (OGAC and RAC-O) were smoother in high temperature regions than in low temperature regions.
6. The IRI of dense- and gap-graded pavements was correlated with increasing MPD, whereas there was little correlation of MPD with IRI on open-graded mixes._The monitoring performed to date shows that traffic volume significantly affects IRI only on RAC-G pavements, with higher truck traffic volumes showing greater IRI values**.**

3 SURFACE MACROTEXTURE RESULTS: MEAN PROFILE DEPTH

Macrotexture was measured using a high-speed profilometer in the right wheelpath, and was collected in terms of mean profile depth (MPD) and the root mean square (RMS) of profile deviations. Because MPD and RMS are highly correlated, only MPD was analyzed in this report.

Figure 3.1 shows the MPD measured over six consecutive years for pavement sections of the four mix types: DGAC, OGAC, RAC-G, and RAC-O. MPD was expected to increase with pavement age, as raveling is caused by removal of particles from the surface by traffic with time, and this expectation was confirmed, as the figure shows MPD generally increased with age for each pavement section.

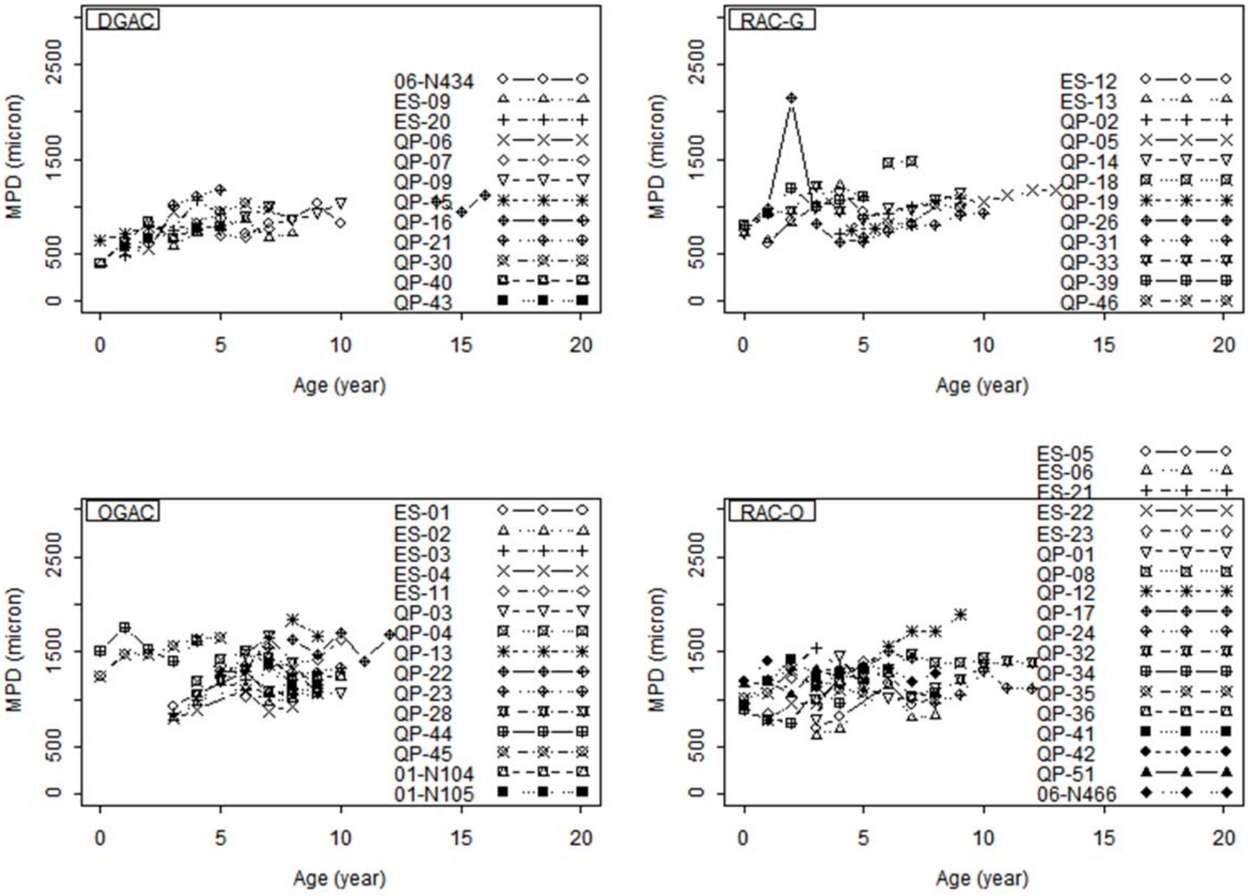

Figure 3.1: MPD trends over six years for each pavement section.

Details of both the descriptive and statistical analyses are presented in Appendix A.3. The following findings were obtained regarding macrotexture:

1. Among all the mixes investigated, OGAC had the highest MPD. The RAC-G mixes had higher MPD values than the dense-graded mixes, and the open-graded mixes had higher MPD values than the RAC-G mixes. Of the two open-graded mixes, the OGAC mixes had higher MPD values than the RAC-O mixes.
2. The R^2 for the RAC-G model is very low, because the RAC-G mixes show a non-linear trend versus age with higher initial MPD followed by a reduction under traffic and then a gradual increase later on, with the later gradual increase indicating little propensity to ravel. The R^2 of the models for the other three mixes are all above 0.60. The OGAC mixes showed the greatest change in macrotexture over their service lives, indicating that they have the highest propensity for raveling over time.
3. MPD generally increased with pavement age. For the open-graded mixes, the effect of age on macrotexture was more prominent on nonrubberized mixes (OGAC) than on rubberized mixes (RAC-O). The growth rate (with age) of MPD was significantly higher on OGAC pavements than on DGAC, RAC-G, and RAC-O pavements. The MPD growth rates of RAC-G and RAC-O pavements were not statistically different from those of DGAC pavements.
4. Within each mix type, air-void content did not have a significant effect on the value of MPD.
5. Fineness modulus significantly affected the macrotexture of dense-graded mixes, with coarser gradations having higher macrotexture, but was insignificant for the RAC-G and OGAC pavements.
6. Layer thickness was only significant on RAC-O pavements. Thicker RAC-O layers had higher macrotexture, which is likely due to the larger maximum aggregates sizes (NMAS) being used with the thicker layers.
7. The MPD of rubberized mixes was significantly affected by the number of days that the temperature is greater than 30°C at a significance level of 10 percent.

4 TIRE/PAVEMENT NOISE RESULTS: ON-BOARD SOUND INTENSITY

Tire/pavement noise was measured in all six survey years using OBSI-California, a version of the on-board sound intensity method that was developed in California. Since OBSI-California was continually developed as the study proceeded, some of its elements changed from one year to the next, and this required that some corrections be made to standardize the data collected over the course of the project. Specifically, two Aquatred 3 test tires (designated as Aquatred 3 #1 and Aquatred 3 #2) were used in the first and second years, while four standard reference test tires (designated as SRTT#1, SRTT#2, SRTT#4, and SRTT#5) were used in the third, fourth, fifth, and sixth years, respectively. A Larson Davis real-time sound analyzer was used in the first three years but was replaced with a Harmonie sound analyzer starting in the fourth year. Because these variations affected the measured OBSI values to varying degrees, calibration equations were developed based on a series of field experiments to standardize the OBSI measurements for each year to a reference condition. A summary of the field experiments and the development of the calibration equations are presented in Appendix B.2. As an example, the overall OBSI calibration for two of the standard reference test tires (SRTT#1 and SRTT#5) is illustrated in Figure 4.1.

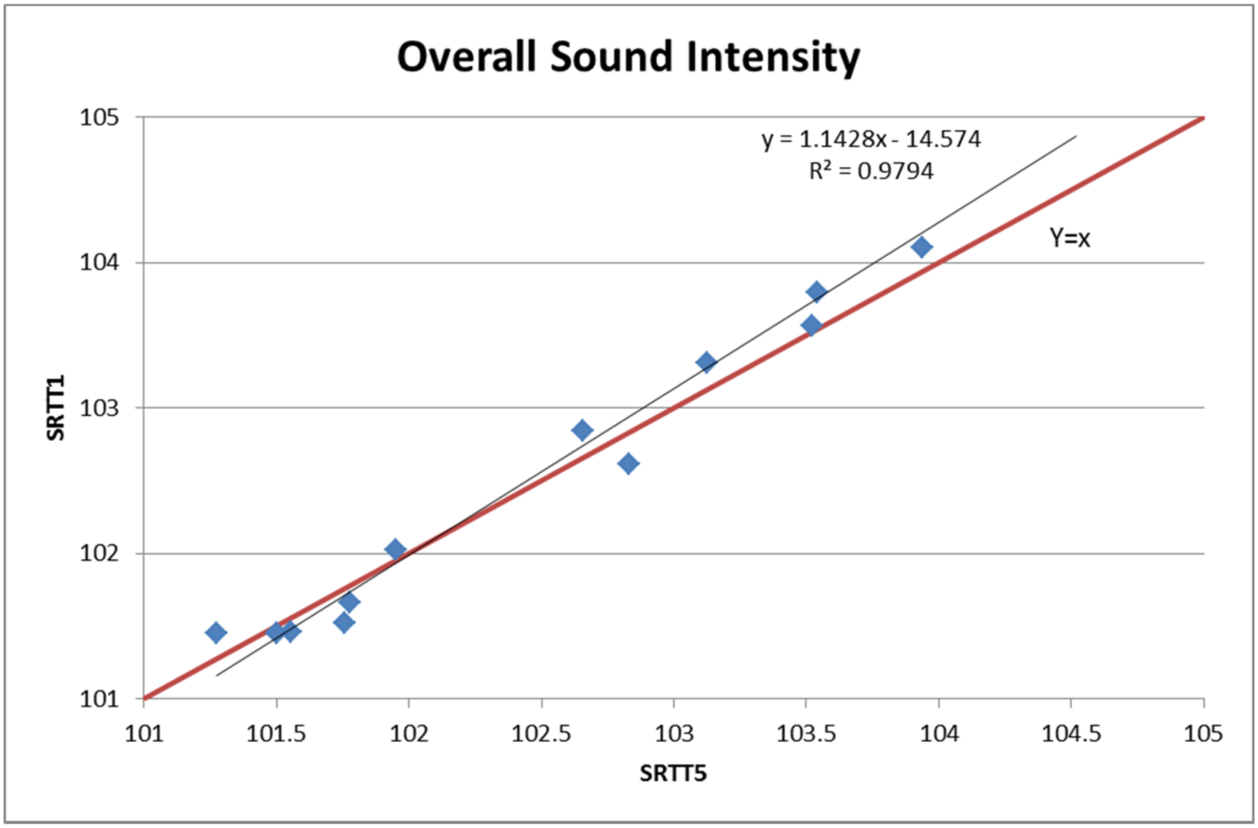

Figure 4.1: Comparison of the overall OBSI values measured with SRTT#1 and SRTT#5.

Using the calibration equations, which were based on linear regression analysis, all the sound intensity measurements were calibrated to their equivalent values at the reference condition: 60 mph test car speed, Harmonie equipment, and SRTT#1. In the two-year and three-year study reports *(2, 3)*, OBSI values were measured at a speed of 30 mph (48 km/h) on a few sections and the results were then converted to their equivalent values at 60 mph (97 km/h) using calibration equations developed in the first two-year study report *(2)*. Given the small number of sections on which the test speed was 30 mph and the potential for large errors to be introduced from the calibration for speed, UCPRC and Caltrans decided to exclude all 30 mph OBSI measurements from the analyses in subsequent years *(4)*. Pavement temperature corrections developed from the experiments were also excluded because the standard error of the calibration equation was large relative to the size of the temperature correction.

The same air-density correction equations that were used in the first two years were also applied to the data in years three through six to account for the differences caused by variations in air density (a function of air temperature, humidity, and altitude) *(2)*. In addition, all the subsequent analyses and modeling were based on OBSI values recalibrated for tire type, analyzer, and air density.

For this six-year report, both the overall sound intensity and the sound intensities at one-third octave frequency bands were analyzed. Figure 4.2 shows the overall OBSI values observed in the six survey years on each pavement section of each of the four mix types. Figure 4.3 shows box plots of the overall OBSI over six years for the different mix types broken down by the three original age categories: less than one year, one to four years, greater than four years.

Figure 4.4 shows the estimated cumulative distribution functions of overall OBSI for the four mix types based on the six years of collected data. Figure 4.5 through Figure 4.7 show the sound intensity spectra averaged by mix type and age group over the six survey years. Generally, overall sound intensity increased with pavement age for all the surface mix types. For all the pavements that ranged in age from newly paved up to about 13 years in service, DGAC mixes were the noisiest and RAC-O mixes were the quietest, with OGAC and RAC-G having roughly similar noise performance over the six years of measurements.

In order to develop prediction models for tire/pavement noise, regression analysis was conducted to determine the effects of mix properties, traffic, and weather conditions on sound intensity levels. In the earlier years of the study, models were developed that considered a number of surface condition distresses. This was changed in the models developed in later years, however, because of variability in the year-to-year assessment of distresses other than raveling. Raveling was measured in terms of MPD by using automation while other distresses were measured by human visual observation. As a result, a decision was made that later versions of the models would only use MPD to indicate the pavement surface condition. As a consequence of that decision, raveling is the only surface condition distress considered in these models.

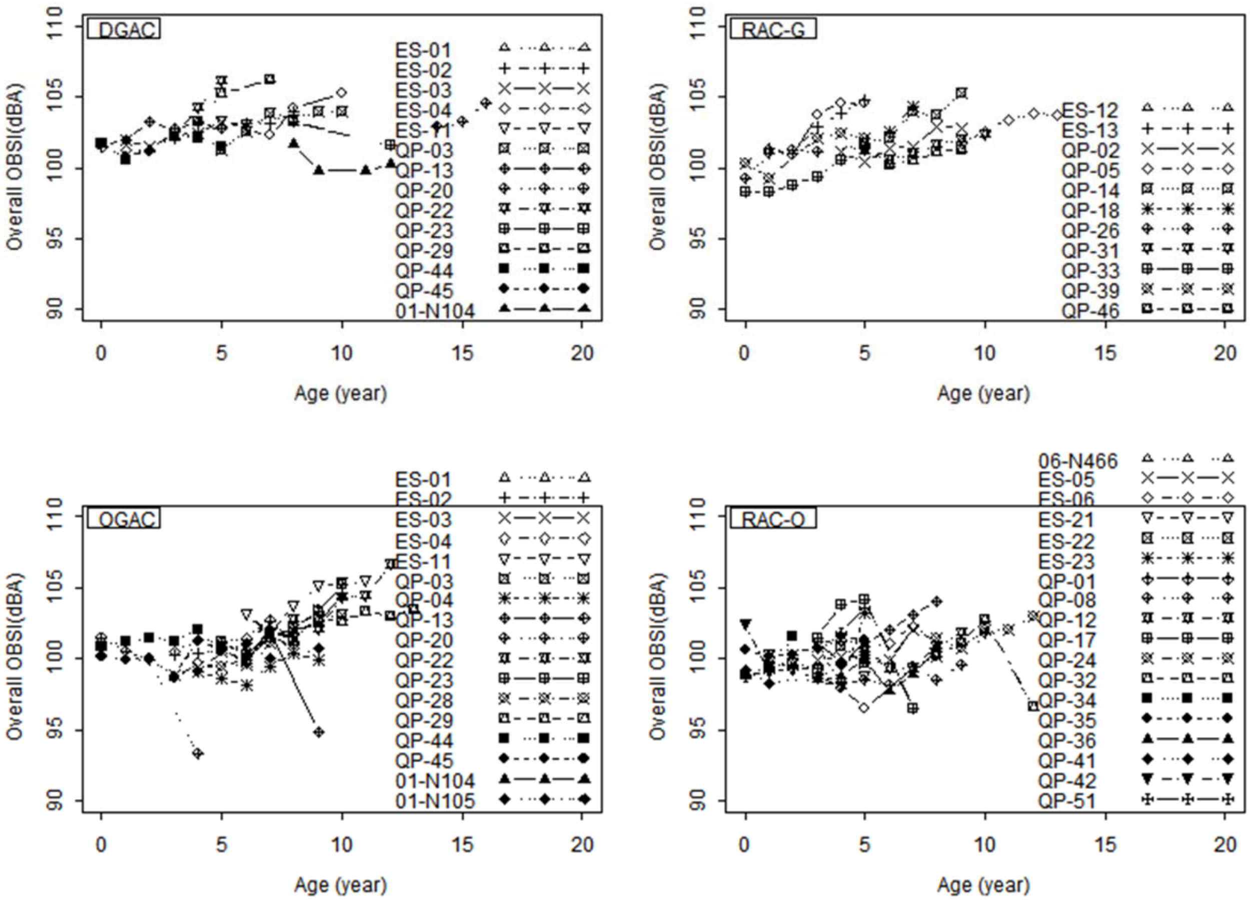

Figure 4.2: Trends of overall OBSI over six years for each pavement section.

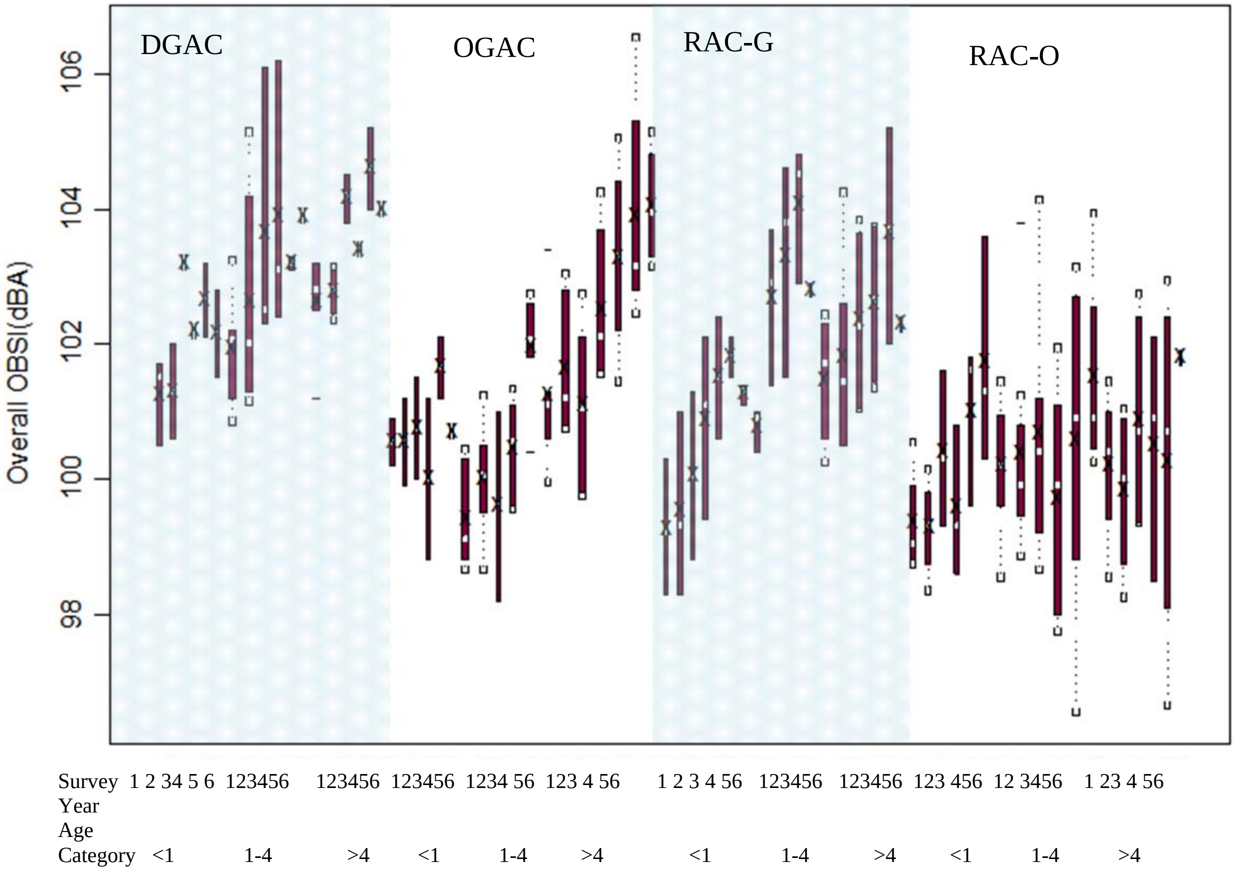

Figure 4.3: Distribution of overall OBSI values for the different mix types by initial age category (Age Category) for the six years of data collection.

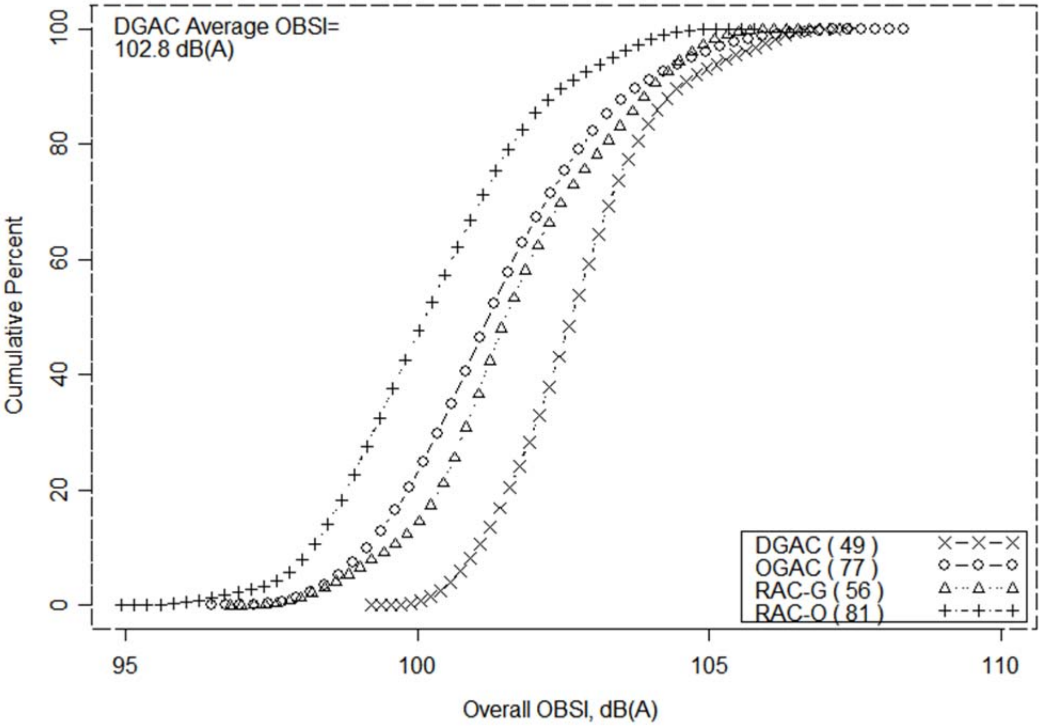

Figure 4.4: Cumulative distribution function of the overall OBSI of the DGAC, OGAC, RAC-O, and RAC-G mixes over six years of measurement.
(Note: numbers in parentheses within the legends represent the sample size of each mix type.)

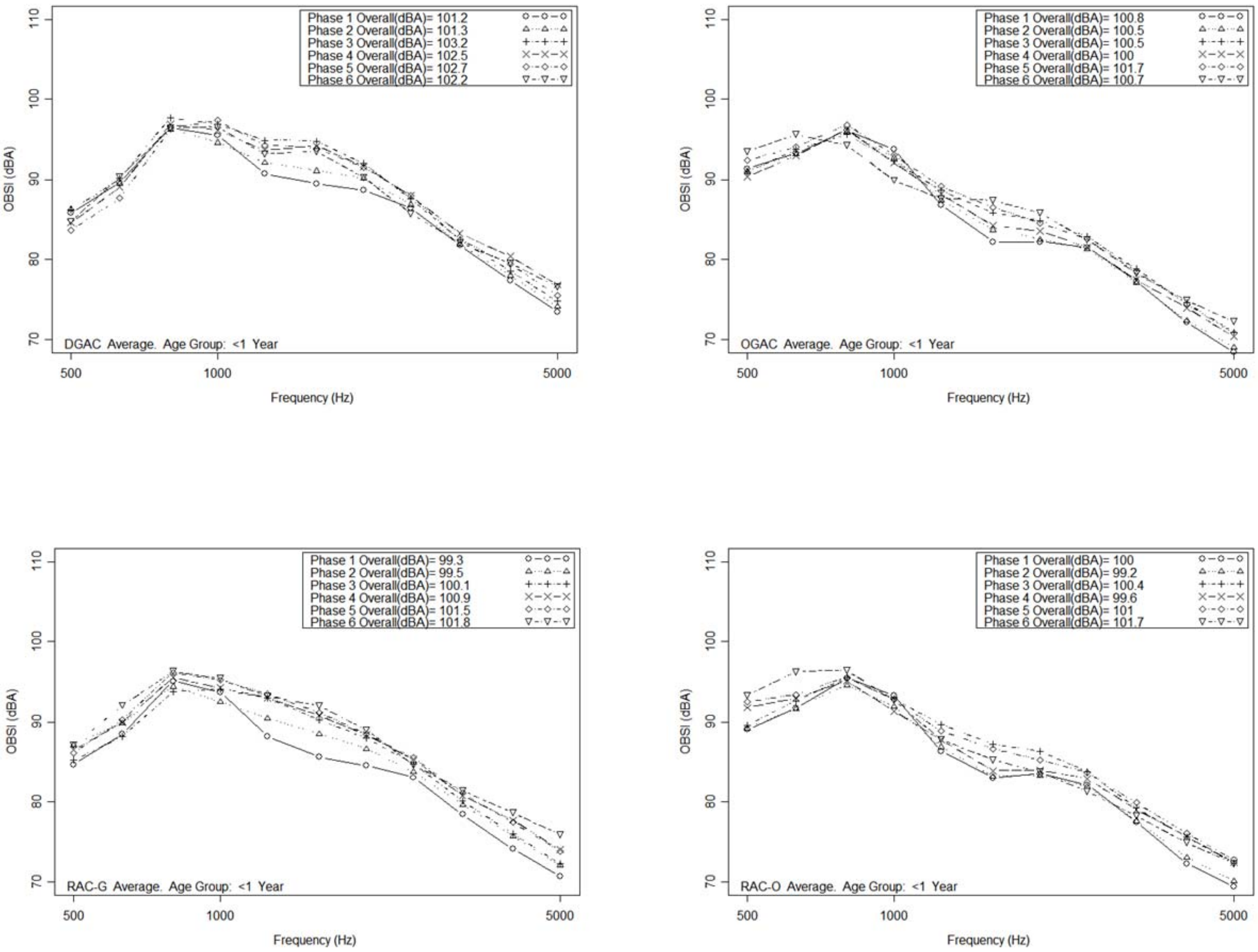

Figure 4.5: Average OBSI spectra for the Initial Age Group "<1 Year" in the six survey years. (Note: average overall OBSI values are shown in the legend.)

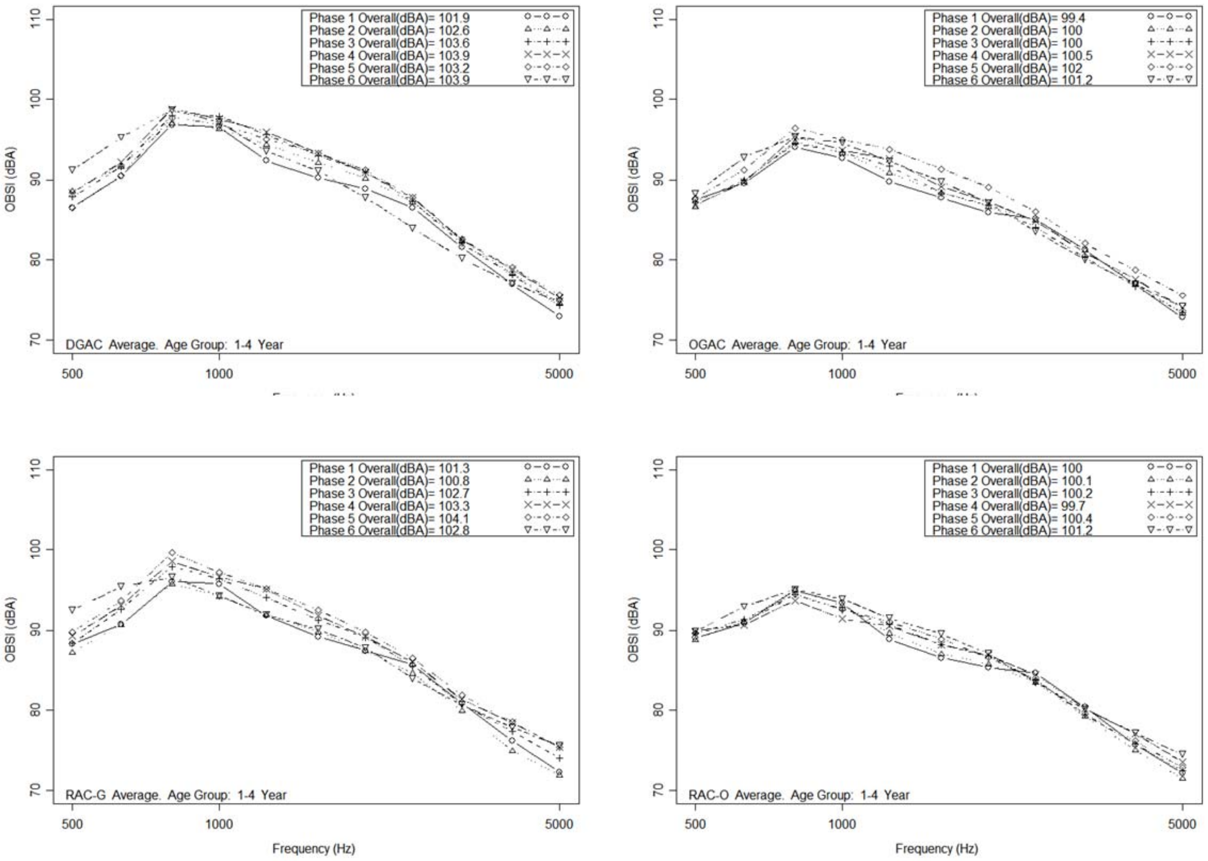

Figure 4.6: Average OBSI spectra for the Initial Age Group "1–4 Years" in the six survey years. (Note: average overall OBSI values are shown within the legend).

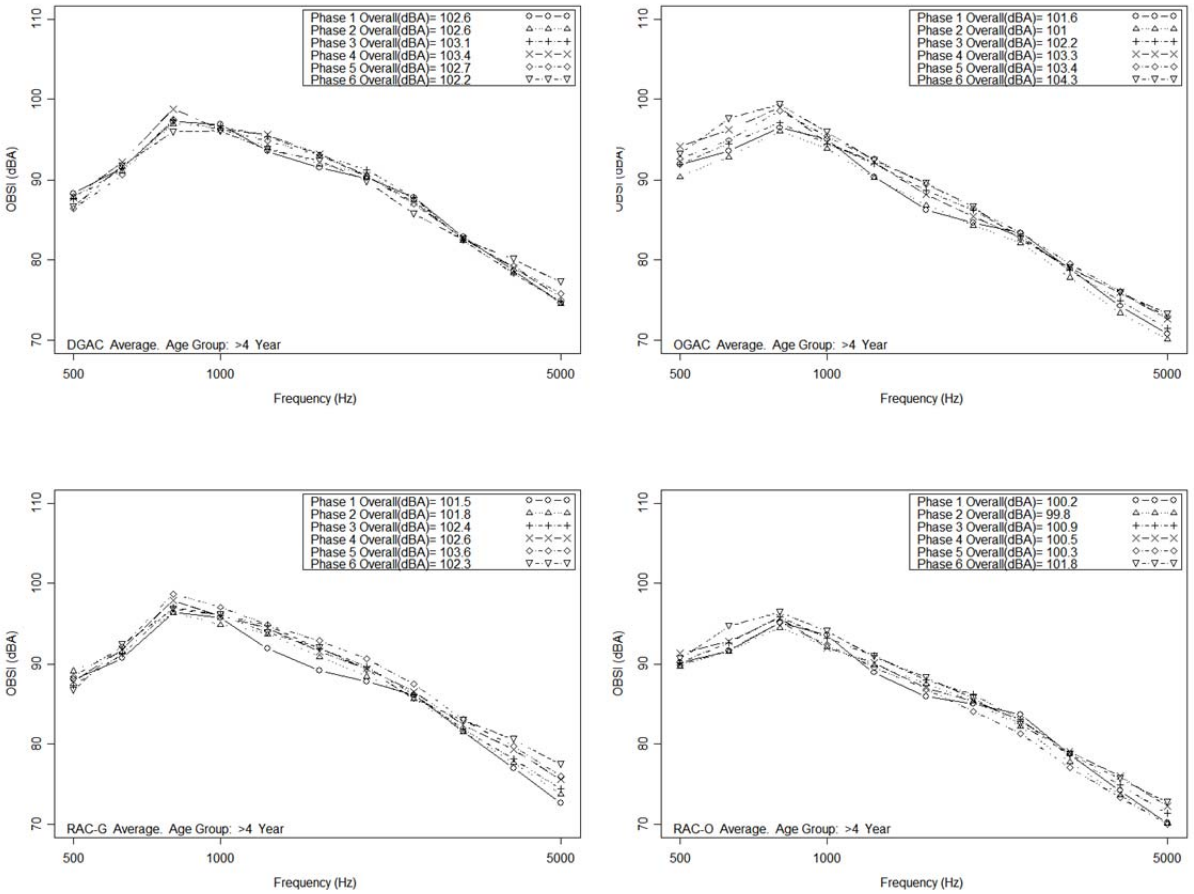

Figure 4.7: Average OBSI spectra for the Initial Age Group ">4 Years" in the six survey years. (Note: average overall OBSI values are shown in the legend.)

Details of the analysis and modeling are presented in Appendix A.4, and the findings are summarized below. Models for all the mixes combined and for each of the four individual mixes with their properties are included in Appendix A.4 for overall sound intensity and sound intensity at a number of one-third octave band frequencies.

The following findings were obtained regarding overall sound intensity:

1. Based on statistical analysis, for newly paved overlays, the overall sound intensities measured on OGAC, RAC-G, and RAC-O pavements were lower than the values measured on the DGAC pavements.
2. According to the model and not accounting for other variables, the average noise reductions (compared to DGAC pavements) for the OGAC, RAC-G, and RAC-O mixes over the lives of the test sections were approximately 3.5 dBA, 1.5 dBA, and 2.6 dBA, respectively. After the pavements were exposed to traffic, the overall sound intensity measured on RAC-G pavements rapidly increased, most likely due to postconstruction compaction from traffic, and became similar to what was measured on DGAC pavements of similar ages.

3. Based on the estimated trend of OGAC sound intensities, the overall sound intensity measured on the OGAC pavements is estimated not to change much for about six to eight years and then to increase at a faster rate with pavement age.
4. Based on the estimated trend of RAC-O sound intensities, the overall sound intensity measured on the RAC-O pavements is estimated not to change much for about ten years and then to increase at a faster rate with pavement age.
5. The ranking (from best to worst) of the four mix types in terms of overall noise reduction is RAC-O, OGAC, RAC-G, and DGAC.
6. Multiple regression analysis on all the mixes shows that overall sound intensity increases with pavement age for all the mix types but that age is only significant for the OGAC and RAC-O mixes. At the 95 percent confidence level, the in-situ permeability is a significant factor only for RAC-G pavements. The surface layer thickness is significant only for RAC-O, possibly due to the fact that for the other mix types the thicknesses were typically similar. Thicker RAC-O mixes produce lower overall noise levels than thinner ones. Pavement surface macrotexture (MPD) is a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. For OGAC and RAC-O pavements, MPD does not have a significant influence on noise level. For all the mix types, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. Truck traffic volume is a significant factor that increases tire/pavement noise for OGAC and DGAC mixes. The rubberized mixes are not as sensitive to truck traffic. For RAC-G mixes, the number of high temperature days per year is significant, and the estimated coefficient (0.0095) indicates that tire/pavement noise increases when the number of high temperature days increases.

Findings regarding sound intensity at one-third octave bands can be found in Appendix A.4.4:

5 ENVIRONMENTAL SECTIONS RESULTS

In addition to the sections for the main Quieter Pavement (QP) factorial, Caltrans also constructed 23 special test sections for the experiment. These sections, called Environmental Sections (labeled "ES" in this study, and so-named because they were primarily selected by the Caltrans Division of Environmental Analysis for monitoring as part of this study), were outside of the main Quieter Pavement (QP) factorial but were also to be tested for pavement noise, durability, permeability, and the friction performance trends of new types of surface mixes. The ES sections included both new types of asphalt mixes—such as gap-graded mixes with modified binders (Type G-MB), dense-graded mixes with modified binder (Type D-MB), and non-Caltrans rubberized mixes (RUMAC-GG, and EU gap-graded)—and currently used mixes—OGAC, RAC-O, DGAC, and RAC-G—that were placed as controls at some locations. Later, eight sections paved with bituminous wearing course mixes (BWC mix type) were also added to the experimental program. For more information, see Appendix B.1. Detailed descriptions of the mixes are included in the Year 3 noise study report *(3)*. From the initial ES sections and the later BWC sections, eight sections were selected to be measured in the sixth and last year of data analysis.

The six years of survey data were pooled to analyze the performance trends of several pavement-related factors such as noise, ride quality, and macrotexture for the various experiments included in the ES sections. Details of the analysis are included in Appendix A.5, and the findings are summarized below:

- Based on the analysis reported after five years of data collection (*5*), on the Fresno 33 sections (which were seven years old when the last data was collected), the RAC-G and Type G mixes generally exhibited the highest and lowest MPD values, respectively. The RAC-G and RUMAC-GG mixes exhibited higher IRI values than the Type G-MB, Type D-MB, and DGAC mixes. There was no indication of the effect of the layer thickness on IRI and MPD. In the fifth survey year, tire/pavement noise increased significantly on the RAC-G 45 mm, DGAC, and RUMAC-GG 45 mm mixes. The RAC-G 45 mm mixes exhibited the highest noise level, 104.7 dBA, and the Type G-MB 45 mm mixes exhibited the lowest noise intensity, 102.7 dBA. Over the long run, none of these mixes appear to provide any noise reduction compared to the DGAC mix.
- Based on five years of data collection analysis previously reported (*5*), the San Mateo 280 section (10 years old at time of last measurement) performed better than the Sacramento 5 (seven years old at time of last measurement) sections in terms of both noise and roughness after five years, possibly due to its thicker RAC-O layer and lower truck traffic. The RAC-O pavement placed on the Sacramento 5 northbound exhibited a major increase in IRI and noise in the fifth year.

- From the LA 138 test sections (10 years old in the sixth year of measurement), it was found that the RAC-O mixes had the lowest IRI and OBSI values. The OGAC mix had a low noise level compared to the DGAC mix, but it exhibited a major increase in overall sound intensity in the sixth year. No interaction between noise-reducing properties and thickness was observed.
- Analysis of the data collected after five years (*5*) showed that the EU-GG mix performed relatively well in terms of providing sound-reducing benefits. The year-to-year increase in IRI for these mixes was not significant.
- Based on six years of data and analysis, the OGAC on the Yolo 80 section, which at the time was 13 years old, still provides good ride quality (according to FHWA guidelines) but has lost its noise-reducing capabilities. The noise spectra of this section indicate that the increase in noise mainly occurred at frequencies lower than 1,000 Hz, indicating raveling, but the increase also occurred at higher frequencies, indicating loss of air permeability.
- Almost all the BWC sections , which were five to seven years old in the last year of measurements (other than the BWC on LA 138, which was not considered representative of typical design and construction), provided ride quality classified as “good” by the FHWA standards for interstate pavements. While the initial noise levels of the BWC sections were lower than those of the other mix types, the sixth year data showed that BWC sections had no noise benefit over DGAC mixes. The increase in sound intensity of the BWC mixes occurred in both the low and high frequency bands. Polymer-modified, open-graded BWC mixes rapidly lost their noise-reduction advantage after five to seven years of traffic, whereas polymer-modified, gap-graded BWC mixes could maintain their noise-reduction advantage for a longer period. Placement of a BWC open-graded mix over an open-graded mix resulted in worse noise performance than placement on a conventional DGAC mix. In the long run, no noise reduction benefit was found for the BWC mix type compared to DGAC.

6 ESTIMATED PERFORMANCE OF DIFFERENT ASPHALT MIX TYPES BASED ON PERFORMANCE MODELS

The regression models for performance developed as part of this study (which are presented in Appendix A) used all the data collected over the six years of the study to estimate the lifetimes of the different mixes with respect to the following performance criteria: roughness (IRI) and tire/pavement noise (OBSI). This chapter presents estimates of the time to failure for the different mixes under different climate and traffic conditions using the respective regression models.

As discussed earlier in this study, data collected over the first two years were used to develop performance models for the permeability and friction (measured in terms of British Pendulum Number, BPN) of both open-graded and gap-graded mixes. But results from these early models indicated that those variables do not control the lifetime of the two mix types *(1, 2)*. Instead, it was generally found that it takes nine years or more for the permeability of open- and gap-graded mixes to decrease to the level of dense-graded mixes. In addition, the friction model provided inaccurate estimates of the lifetime of the mixes because it lacked the variable *aggregate type*. In any case, since friction was not found to be a problem for the California mixes evaluated in the two-year study *(1, 2)*, and no friction measurements were taken in the third and fourth survey years, the current performance models have not been updated to include friction.

6.1 Prediction of IRI

In Appendix A.2, two regression models were estimated for roughness (IRI). The first model contains the mix type (categorical variable), and environmental and traffic factors as independent variables, while the second model contains the mix property variables as independent variables. Both models can be used to estimate the average lifetime of each mix type, but the first model is easier to use because it does not need the mix characteristics as inputs.

Equation A.2.1 shows that the average annual rainfall, number of days with temperature higher than 30°C, truck traffic, and number of annual freeze-thaw cycles are statistically significant in affecting IRI. All these factors are continuous variables, which can be used to estimate the roughness of a pavement using any combination of values of these variables. In this section of this report, some typical values of the independent variables have been selected to estimate the time it takes a pavement to reach failure.

Two ten-year Traffic Index (TI) values, 9 and 12, were chosen to represent high and low traffic conditions, respectively. Using a statewide average truck factor of 1.17 ESALs per axle and a compound growth rate of 3 percent—which were estimated from weigh-in-motion data collected from 73 Caltrans WIM sites between 1991 and 2003 *(7)*—the two TI values correspond to 204 and 2,291 AADTT in the design lanes, and ten-year ESALs of 1.0 million and 11.2 million, respectively

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Values for the environmental factors have been selected to represent different climate conditions, as shown in Table 6.1. “Typical” climate data for the four climate conditions were averaged from climate data collected at the QP and ES sections in this study, and then grouped in four environment combinations. The climate data were obtained from the *Climatic Database for Integrated Model (CDIM)* software (*8*).

Table 6.1: Selection of Typical Environmental Regions

Environment	Average Annual Rainfall (mm)	Number of Days with Temperature Greater than 30°C	Annual Freeze-Thaw Cycles
Low Rainfall/ High Temperature	274	117	14
Moderate Rainfall/ Low Temperature	585	33	12
High Rainfall/ Moderate Temperature	1,444	68	32
Moderate Rainfall/ Moderate Temperature	719	68	7

An IRI value of 2.68 m/km (170 in./mi), which is the maximum acceptable value for roughness according to FHWA and the maintenance or rehabilitation trigger value in the Caltrans pavement management system, has been selected as the threshold value for a pavement to reach failure. Table 6.2 shows the estimated ages to reach this threshold value for each mix type in different traffic and climate combinations calculated using the model. Rubberized mixes retain “acceptable” riding smoothness longer than non-rubberized mixes. Open-graded mixes retain acceptable riding smoothness longer than dense- or gap-graded mixes. Roughness also increases more slowly on pavements in low rainfall/high temperature regions than in high rainfall/moderate temperature regions. Higher truck traffic volume significantly shortens pavement life by about one to two years in terms of roughness.

Table 6.2: Predicted Lifetime of Different Asphalt Mix Types with Respect to Roughness Using the General Model

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	15	17	15	>15
	Moderate Rainfall/ Low Temperature	9	11	8	16
	High Rainfall/ Moderate Temperature	8	11	11	16
	Moderate Rainfall/ Moderate Temperature	9	12	10	16
Low Traffic (TI=9)	Low Rainfall/ High Temperature	12	17	15	>15
	Moderate Rainfall/ Low Temperature	10	12	11	16
	High Rainfall/ Moderate Temperature	11	12	10	15
	Moderate Rainfall/ Moderate Temperature	10	12	11	15

Note:
Since the oldest sections in the sample are approximately 15 years old, calculated values greater than 17 years are shown as >15, values greater than 20 years are shown as >>15, and values greater than 25 years are shown as >>>15. Actual values predicted by all models with values greater than 15 years are shown in Table B.19 in Appendix B.6.

6.2 Prediction of Tire/Pavement Noise

In Appendix A.5, two types of regression models were estimated for overall tire/pavement noise, as measured by on-board sound intensity (OBSI). The first model (Equation A.5.2) contained the mix type, MPD, and environmental and traffic factors as independent variables, while the second model (Equation A.5.3 through Equation A.5.6) was estimated for each individual mix type to explore the effects of mix property variables such as permeability, fineness modulus, MPD, and thickness on noise. *Pavement noise performance life* for the open- and gap-graded mixes, in terms of noise reduction, was defined as the time it would take the OBSI of the mix to reach the level of a typical DGAC pavement with an age of one to three years. The second set of models, those for the individual mix types, were used to estimate pavement performance life in terms of noise as opposed to noise reduction**.** Results from the second model were expected be more accurate than the first because this model was estimated from individual mix data. The independent variables for this model included pavement age, permeability, fineness modulus, MPD, surface layer thickness, number of days with temperature higher than 30°C, and AADTT in the coring lane. The same values for surface layer thickness, traffic, and environmental variables that were used in the IRI model were used here. Permeability and MPD both change with pavement age and were estimated from the regression models developed in this study as input into the noise model. The estimated ages for the open- and gap-graded mixes calculated using the models are shown in Table 6.3.

It can be seen in the table that the number of years it would take the various mixes (OGAC, RAC-G, and RAC-O) to reach the equivalent noise level of a DGAC pavement with an age of one to three years differed significantly, but differences caused by various traffic and environmental conditions were not as important. The relative ranks of the three mixes remained the same as the RAC-O mixes remained quieter longer than the OGAC mixes did, and the OGAC mixes remained quieter than the DGAC mixes for a longer time than the RAC-G mixes did.

Table 6.3: Predicted Lifetime of Different Asphalt Mix Types with Respect to Noise from Models for Individual Mixes

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	–	9	5	15
	Moderate Rainfall/ Low Temperature	–	9	8	14
	High Rainfall/ Moderate Temperature	–	8	6	14
	Moderate Rainfall/ Moderate Temperature	–	9	6	13
Low Traffic (TI=9)	Low Rainfall/ High Temperature	–	9	6	14
	Moderate Rainfall/ Low Temperature	–	10	9	13
	High Rainfall/ Moderate Temperature	–	11	7	13
	Moderate Rainfall/ Moderate Temperature	–	10	7	14

Note: Since the oldest sections in the sample are approximately 15 years old, calculated values greater than 17 years are shown as >15, values greater than 20 years are shown as >>15, and values greater than 25 years are shown as >>>15. Actual values predicted by all models with values greater than 15 years are shown in Table B.20 in Appendix B.6.

Since the pavement life for open- and gap-graded mixes in terms of noise reduction is defined as the time it takes the OBSI to reach the level of a typical DGAC pavement with an age of one to three years, the values in Table 6.3 will increase if the noise level on a DGAC pavement with an age of over three years is used as the criterion, and will decrease if the noise level on a newly paved DGAC surface is used as the criterion.

7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1. Summary

This study compares six years of pooled field data gathered on California pavements with conventional or polymer-modified open-graded (OGAC), rubberized open-graded (RAC-O) and rubberized gap-graded (RAC-G) asphalt surfaces with data collected on conventional dense-graded asphalt concrete (DGAC).[4] Over the six years of measurements, data were collected to examine tire/pavement noise, ride quality, and macrotexture. At different times over the course of the study, and finally in this sixth year report, the data were analyzed to accomplish the following three objectives:

1. To evaluate the effectiveness of the OGAC, RAC-O, and RAC-G asphalt mix types in reducing noise compared with DGAC, as measured with the On-board Sound Intensity (OBSI) method
2. To evaluate the pavement characteristics that affect tire/pavement noise
3. To evaluate the changes in the following pavement performance parameters over time and to develop prediction models for estimating future performance:
    - Smoothness, in terms of International Roughness Index (IRI)
    - Macrotexture, in terms of mean profile depth (MPD)
    - Tire/pavement noise, in terms of OBSI

Two types of models were developed. In the first type, data for all the mixes were pooled and then models were developed. In the second type, models were developed for the individual mixes using data collected on them over all six years. MPD was introduced into the individual models as an indication of raveling.

7.2. Conclusions

7.2.1. Performance of Open-Graded Mixes

For newly paved DGAC overlays, the average tire/pavement noise level was approximately 101.3 dBA. The study results showed that average tire/pavement noise levels for newly paved overlays with OGAC, RAC-G, and RAC-O open-graded mixes were lower than those of the DGAC mixes by median values of approximately 0.1 dBA, 1.0 dBA, and 1.9 dBA, respectively.

After the pavements were exposed to traffic, the OGAC noise benefit generally diminished slightly for about six to seven years. The noise-reduction benefit lasted longer for RAC-O than for OGAC, and RAC-O remained quieter than DGAC of the same age for between 10 and 11 years. However, after nine years, none of the RAC-O sections remained quieter than DGAC sections of the same age by more than 3 dBA. This is important because

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[4] See the footnote on page 2 regarding terminology for pavement types used in this report.

3 dBA has been identified as the threshold value at which most humans can perceive a difference in noise. For this reason, highway noise changes of less than 3 dBA are generally considered to be relatively insignificant (9). It should be noted though that that threshold is based on studies of humans listening to pure tones in a laboratory setting, such as in a common hearing test. Also, many people can hear less than 3 dBA differences in tire/pavement noise and/or perceive differences in the frequency content of two tire/pavement noise sources that have the same sound intensity (as measured in dBA).

The main advantage gained from use of open-graded mixes comes from their ability to reduce high frequency noise because they have high permeability which reduces the air-pumping tire/pavement noise mechanism, and the newly paved open-graded OGAC and RAC-O overlays generally had lower high-frequency noise than the less permeable dense-graded mixes. Macrotexture as measured by MPD, which when it is positive (stones protruding up from surface) has a large influence on low frequency noise through tire vibration, was lower for newly constructed RAC-G and DGAC mixes than for open-graded mixes. Low-frequency noise increased with age, likely due to the increase in surface distresses, primarily raveling as measured by MPD. Increases in low frequency noise contribute to overall noise levels, and the benefits of reduced high frequency noise for open-graded mixes can be offset by increases in low frequency noise. Measured data indicate that OGAC pavements are more prone to development of raveling than RAC-O mixes after six to eight years of trafficking.

The surface types OGAC, RAC-G, and RAC-O all had lower IRI than DGAC over the full data set, but only OGAC and RAC-O were statistically significantly different from DGAC. Monitoring over six years indicates that IRI increases with age on all mix types, but that age had a statistically significant effect in increasing IRI on DGAC and RAC-O at a 5 percent significance level but not on OGAC and RAC-G.

7.2.2. Performance of RAC-G Mixes

The newly paved RAC-G mixes were quieter than an average newly paved DGAC mix by about 1.8 dBA *(1)*. However, the tire/pavement noise on RAC-G mixes approached the average noise level of DGAC pavements of similar ages within three to five years after construction. The main change in noise level occurred at high frequencies. Moreover, the RAC-G mixes had higher low-frequency noise and lower high-frequency noise than DGAC mixes. In the first three years after the pavements were exposed to traffic, high frequency noise increased considerably with age, due to the reduction of surface permeability and air-void content under traffic, while low-frequency noise (equal to or less than 1,000 Hz) was nearly unchanged with age. In sections with severe raveling, the low frequency noise increase quickly and degraded the noise-reduction benefit of the RAC-G pavements.

The IRI values on newly paved RAC-G mixes were somewhat lower than those measured on DGAC mixes. The rate of increase in IRI on newly paved for RAC-G mixes was smaller than on similarly aged DGAC mixes.

The MPD values on newly paved RAC-G mixes were higher than on DGAC mixes. The rate of increase in MPD on old RAC-G was higher than that on similarly aged DGAC.

7.2.3. Performance of Environmental Sections

During the noise study of environmental sections, the noise, ride quality, and surface macrotexture of twenty-one environmental sections were measured, eight of which had continued monitoring in the sixth year. The following conclusions were drawn from the results of this study:

Results obtained from the Fresno 33 sections showed that the RAC-G and Type G-MB mixes generally exhibited the highest and lowest MPD values, respectively. The RAC-G and RUMAC-GG mixes exhibited higher IRI values than the Type G-MB, Type D-MB, and DGAC mixes. No indication could be seen of the effect of layer thickness on the measured IRI and MPD of any of these mixes. The Type G-MB 45 mm thick overlays exhibited the lowest sound intensity, with a value of 102.7 dBA. None of these mixes provided any noise reduction benefit compared to the DGAC mixes after seven years in service.

Of the two sections with thin RAC-O overlays on concrete pavement, the San Mateo 280 section (10 years old at final measurement) performed better than the Sacramento 5 sections (seven years old) in terms of both noise and roughness, possibly due to the San Mateo section’s greater layer thickness and lower truck traffic. The RAC-O pavement placed on the Sacramento 5 northbound exhibited a major increase in IRI.

Results from the LA 138 test sections, which includes sections with the DGAC, OGAC, RAC-O, and BWC mix types, showed that RAC-O mixes had the lowest IRI values noise levels of all these mixes. After the sixth year of measurement, when they were 10 years old, the OGAC mixes showed no significant difference in noise compared with the DGAC mixes. Further, there seemed to be no interaction between surface layer thickness and overall sound intensity after six years.

Results on the LA 19 EU-GG mix up through five years, after which measurements were stopped, showed that it performed well in terms of providing sound-reduction benefits, compared with statewide data collected for DGAC. Although this mix also showed a year-to-year increase in IRI, it was not significant.

The Yolo 80 section is still providing good ride quality according to FHWA guidelines, but it has lost its noise-reducing capabilities, as shown by a comparison with statewide data for DGAC. At its current age of 13 years, the section's overall sound intensity is slightly more than 105 dBA. The noise spectrum of this section indicates that the increase of noise mainly occurred at frequencies lower than 1,000 Hz, an indication of raveling.

Almost all the BWC sections included in this study provided good ride quality. The BWC mixes appeared to provide an immediate noise reduction benefit, and then appeared to lose it by the time of the last measurements when they were five to seven years old. At that time, no noise-reduction benefit from use of BWC was observed compared with new DGAC.

7.2.4. Variables Affecting Tire/Pavement Noise

The findings from this sixth year of the study regarding the variables that affect tire/pavement noise are generally in agreement with the significant factors found in the earlier reports *(2, 3, 4, 5).* Tire/pavement noise is greatly influenced by surface mix type and mix properties, age, traffic volume, and the presence of distresses. Noise levels generally increased primarily with traffic volume and pavement age. Overall noise levels decreased with increased surface layer thickness and permeability (or air-void content) for open-graded mixes.

For all the mix types (DGAC, RAC-G, OGAC, and RAC-O), the aggregate gradation variable (fineness modulus) had an effect on some noise frequencies; however, neither the nominal maximum aggregate size (NMAS) or the gradation significantly affected overall tire/pavement noise within each mix type. It should be noted that this conclusion is based on an analysis of mixes with a limited number of aggregate gradation distributions. Further investigation is required to draw more conclusive results.

Pavement surface macrotexture (MPD) was a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponded to a higher noise level, particularly at lower frequencies. For OGAC and RAC-O pavements, MPD did not have a significant influence on noise level.

7.3. Recommendations

It is recommended that the predictions for noise and IRI developed as part of this study be used along with other Caltrans criteria to determine where the use of quieter pavement is cost-effective. It is recommended that where quieter asphalt pavement is used instead of DGAC as the surface material, that RAC-O be used since it provides better performance with respect to noise and IRI than OGAC or RAC-G.

REFERENCES

1. Ongel, A., J. Harvey, E. Kohler, Q. Lu, B. Steven, and C. 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, University of California Pavement Research Center, Davis and Berkeley, California.
2. Ongel, A., J. Harvey, E. Kohler, Q. Lu, and B. 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, University of California Pavement Research Center, Davis and Berkeley, California.
3. Lu, Q., E. Kohler, J. Harvey, and A. Ongel. 2009. *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results*. UCPRC-RR-2009-01, University of California Pavement Research Center, Davis and Berkeley, California.
4. Lu, Q., J. Harvey, R. Wu. 2011. *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Four-Year Results*. UCPRC-RR-2010-05, University of California Pavement Research Center, Davis and Berkeley, California.
5. Rezaei, A., J. Harvey, Q. Lu. 2012. *Investigation of Noise and Ride Quality Trends for Asphaltic Pavement Surface Types: Five-Year Results*. UCPRC-RR-2012-04, University of California Pavement Research Center, Davis and Berkeley, California.
6. Lu, Q.,Wu, R.Z. and Harvey, J. 2011. Calibration of On-Board Sound Intensity For Test Tire, Speed, Pavement Temperature, and Analyzer Equipment. Proceedings, Noise-Con 11, Institute of Noise Control Engineering of the USA and Transportation Research Board Committee ADC40, Portland, Oregon.
7. Lu, Q. 2008. *Estimation of Truck Traffic Inputs Based on Weigh-In-Motion Data in California*. UCPRC-TM-2008-08, University of California Pavement Research Center, Davis and Berkeley, California. In progress.
8. Mohseni, A. 2004. Climatic Database for Integrated Model—CDIM version 1.0. Software prepared for UCPRC by Pavement Systems LLC (PaveSys), Bethesda, MD.
9. Federal Highway Administration (FHWA). 2011b. *Highway Traffic Noise: Analysis and Abatement Guidance.* FHWA-HEP-10-025.

APPENDICES

APPENDIX A: DETAILS OF SIX-YEAR DATA COLLECTION AND ANALYSIS

A.1: Introduction

This appendix presents the details of data collection and analysis based on the pool of six-year measurement data, including International Roughness Index (IRI), Mean Profile Depth (MPD), and On-board Sound Intensity (OBSI) measurements of tire/pavement noise.

A.2: Surface Profile Results and Analysis: IRI

The analysis of IRI answers these questions:

- What pavement characteristics affect IRI?
    - Are initial IRI and IRI changes with time different for rubberized and non-rubberized mixes?
    - Are initial IRI and IRI changes with time different for open-graded and dense-graded mixes?
- How do traffic and climate affect IRI?

A.2.1: Descriptive Analysis

Figure A.1 is a box plot that represents the IRI values for the different mix types across all six years of measurement. In all of the box plots shown in this report the white bar is the median value, the “X” is the mean value, the upper and lower edges of the colored box are the 75th and 25th percentiles respectively, and the upper and lower brackets are the maximum and minimum values respectively.

The median IRI values of the different mixes were relatively similar, and most of the sections had acceptable IRI values based on the FHWA criterion of 170 in./mi (2.4 m/km) (*1*), which is also the new Caltrans criterion. In the sixth year, some sections showed IRI values high enough to trigger Caltrans maintenance action under the old Caltrans criterion (>3.6 m/km). It should be remembered that sections that were overlaid have been removed from the data set, and that the values shown in the figures represent the effects of the IRI level on the sections at the beginning of the study, local maintenance, and changes in the pool of data due to the removal of some sections from the study.

Figure A.2 shows the variation of IRI values over the six years of measurements for the different mix types divided into the three initial age categories: less than one year, one to four years, and greater than four years. It can be seen from the six years of IRI values that they are greater for the DGAC mixes that were older than 4 years at the start of the study, and do not show as wide a range for the other mixes.

Figure A.3 shows the time trend of IRI across the six years of data collection for the different mix types broken into the three initial three age categories. IRI generally increased with time, although decreases can be seen for some initial age/mix type categories due to the removal of some sections from the experiment. Over the six years, the IRI for newly paved sections (Age Category "<1 year") changed less in six years than it did for other initial age categories. Many of the roughest sections were removed from the older initial age categories in the fourth, fifth, and especially the sixth year of measurements. Older DGAC and RAC-O sections had the highest variation in IRI among the mixes.

As was shown in Figure 2.1, RAC-G sections QP-14 and QP-18, which are located on Interstate-15 in Riverside County in Caltrans District 4 and on Highway 4 in Calaveras County in District 10, respectively, had the highest rates of increase in IRI. Among the DGAC sections, Section QP-09, which is located on Highway 280 in San Mateo County in District 4, showed a significant increase in IRI in sixth year. Due to an abnormal increase that occurred in the third year of data collection, QP-20 and QP-26 were excluded from the data regression analysis; the reason for the rapid increase in IRI at these sections is unknown. Figure A.4 shows the same data as Figure A.3 with sections QP-20 and QP-26 removed.

Note: Metric units were used in the study when it was initiated, and for consistency all the subsequent data was recorded using those same units. For reference, some critical IRI values are shown below in inches per mile *(2):*

Criteria	**in./mi**	**m/km**
FHWA "very good" maximum value	60	0.95
FHWA "good" maximum value	94	1.48
FHWA "fair" for Interstates maximum value	119	1.88
FHWA "fair" for non-Interstates and "mediocre" for Interstate maximum values, and Caltrans current PMS prioritization trigger	170	2.68
FHWA "mediocre" for non-Interstate maximum value	220	3.47
Caltrans previous rigid pavement PMS prioritization trigger	213	3.36
Caltrans previous flexible pavement PMS prioritization trigger	224	3.54

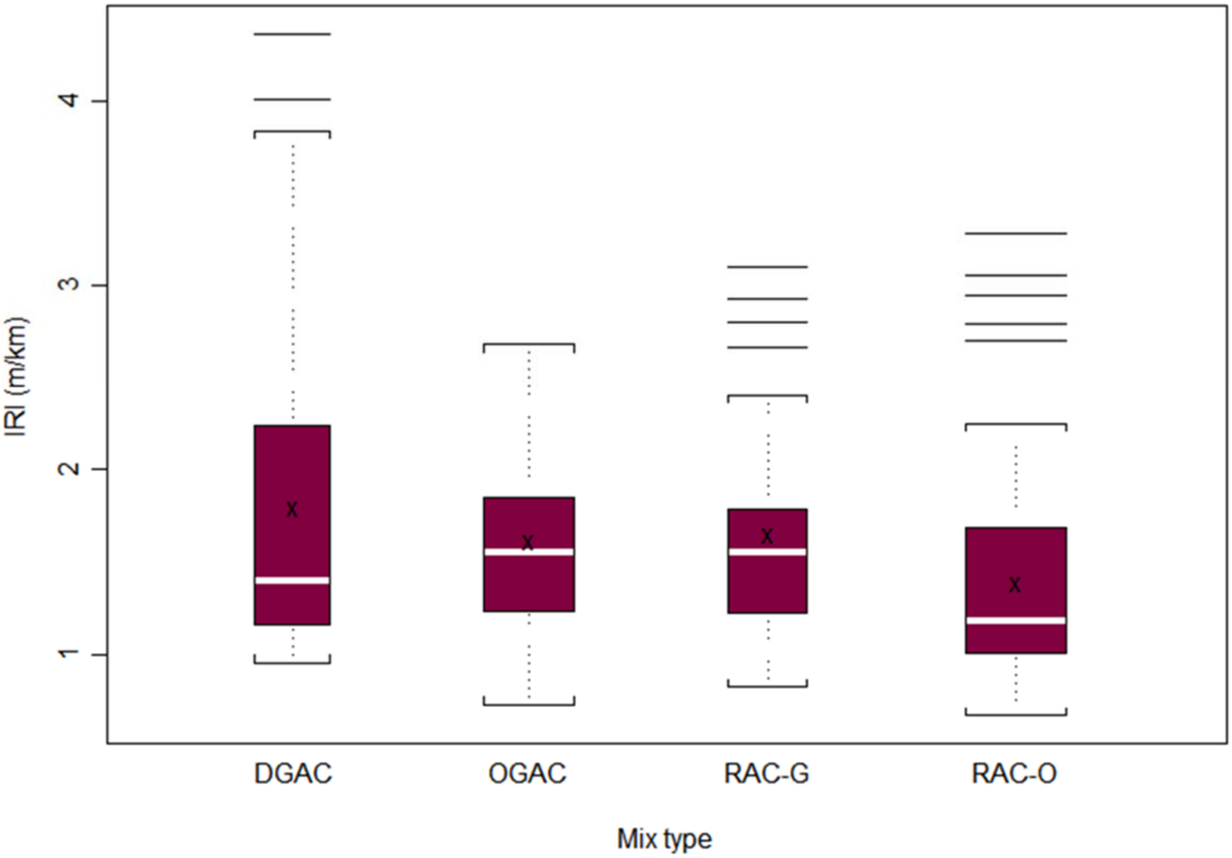


Figure A.1: Distribution of IRI values of the different mix types for all six years of pooled data and all initial ages.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

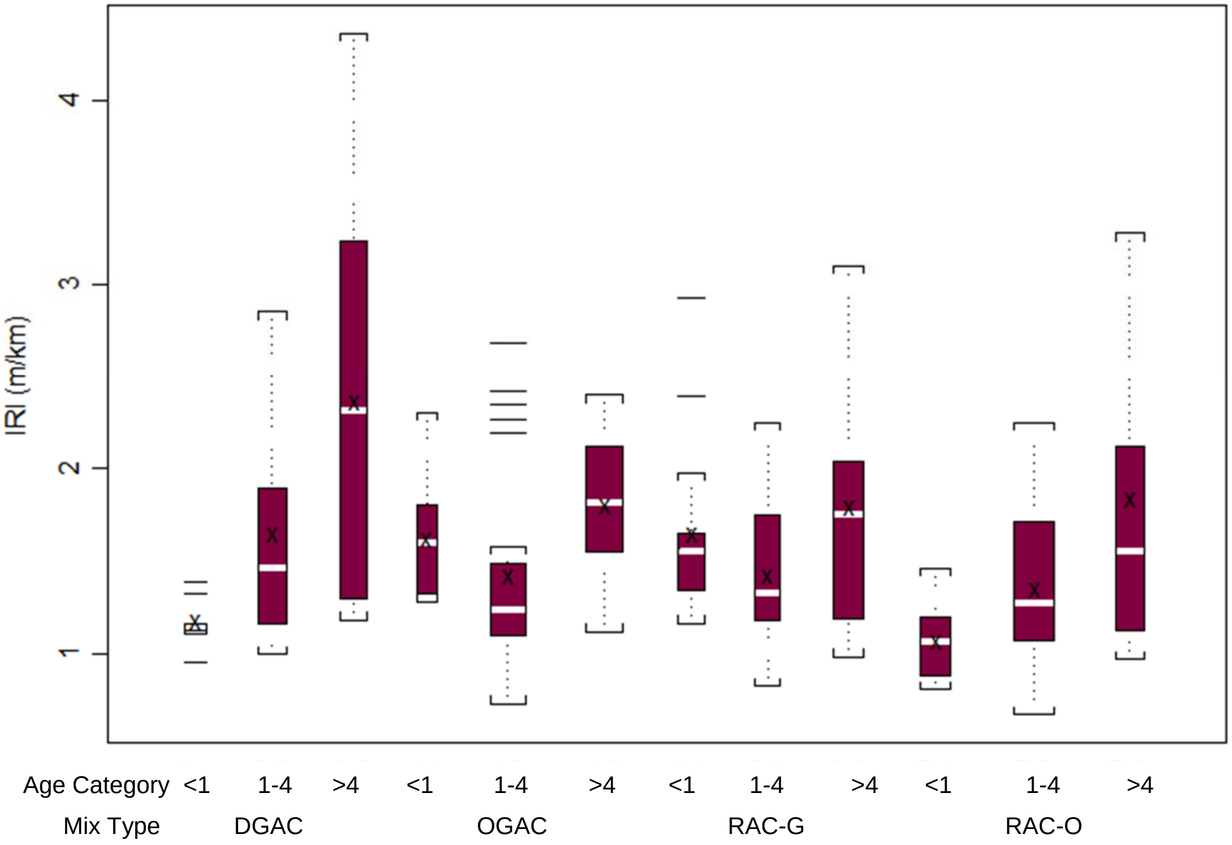


Figure A.2: Distribution of IRI values of the different mix types by different initial ages (Age category in years) for all six years of pooled data.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

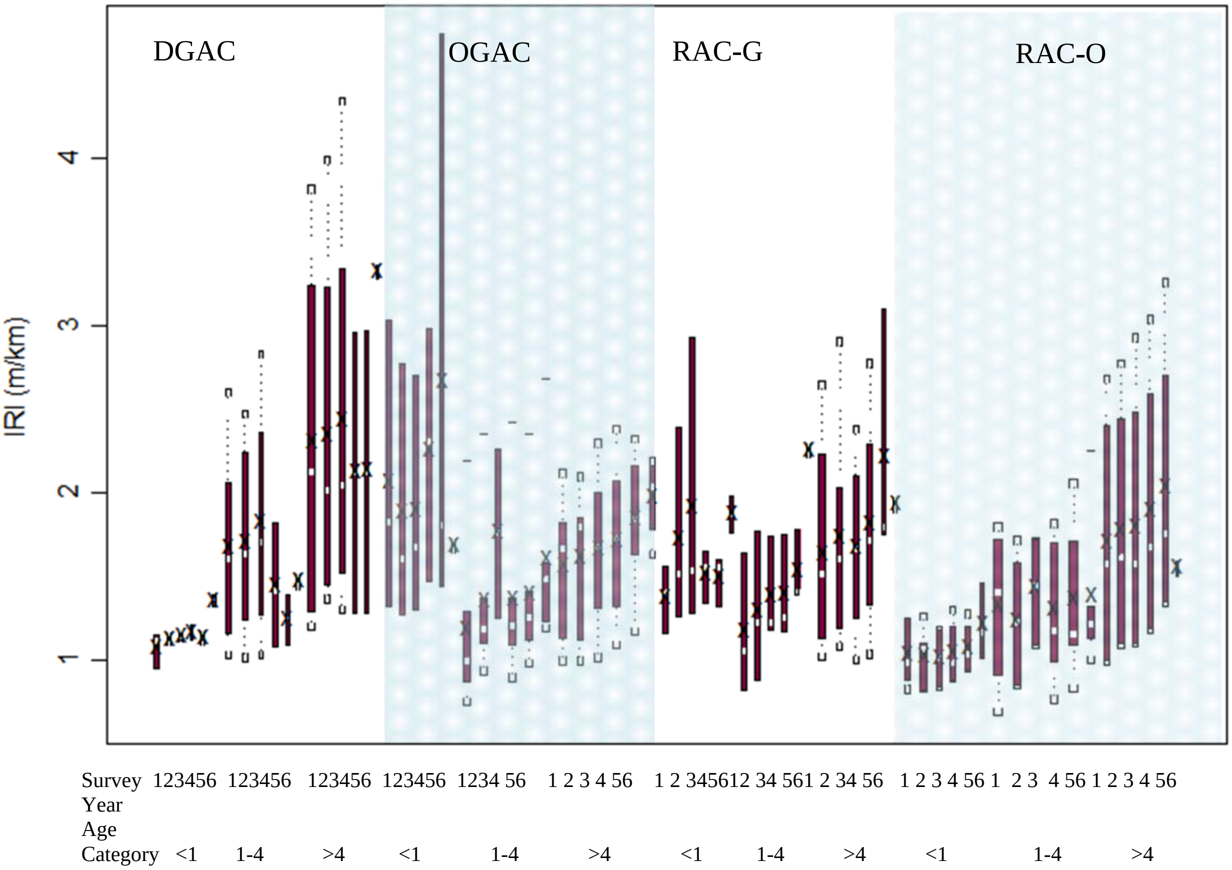


Figure A.3: Distribution of IRI values of the different mix types and different initial ages across the six years of data collection.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

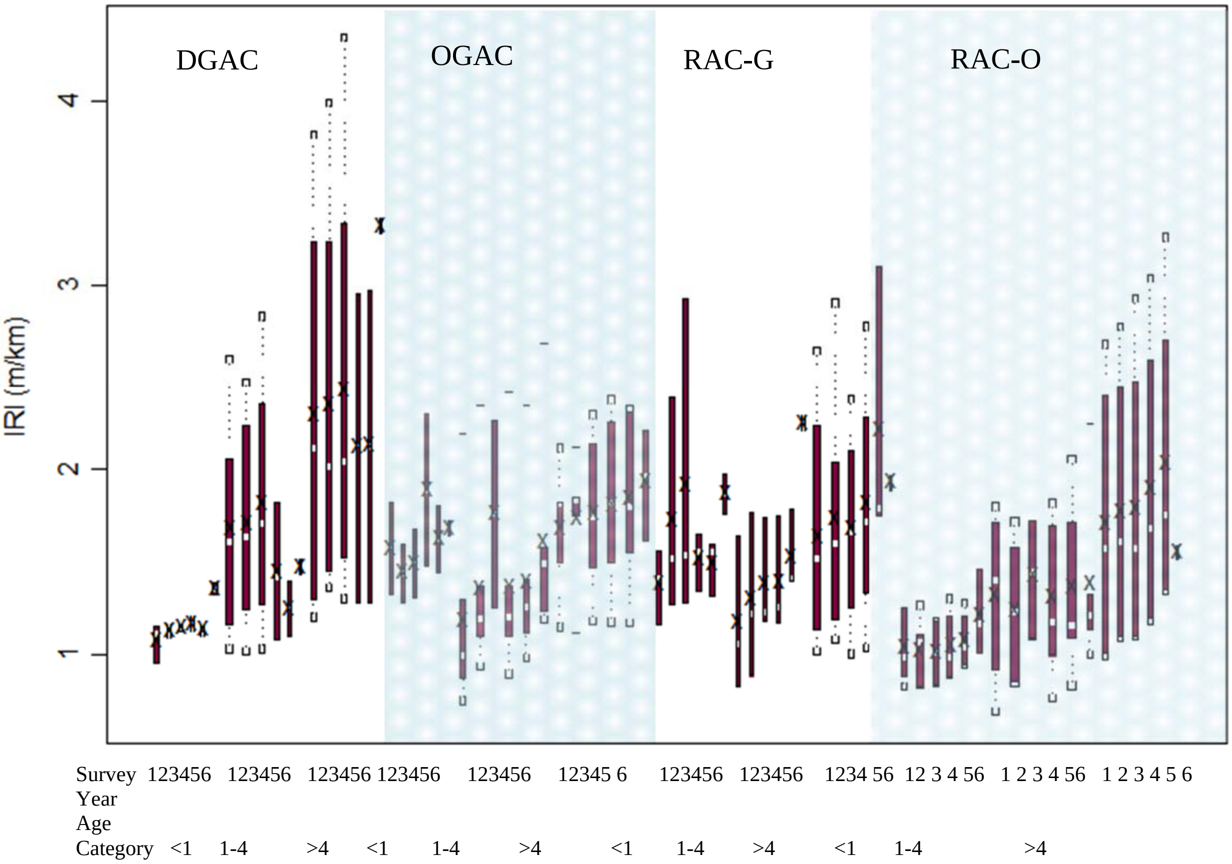


Figure A.4: Distribution of IRI values of the different mix types and different initial ages across six years of data collection after removing QP-20 and QP-26.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

A.2.2: Regression Analysis

Regression analysis was carried out to evaluate the effects of traffic, climate, and pavement materials on IRI values. Since pavement condition data was not available in sixth year of data collection, the effect of surface distress was excluded from the analysis. First, a single-variable regression analysis was conducted to find statistically significant factors to be included in a multiple regression model. Estimates of the coefficient of the explanatory variable and the constant term along with their P-values and the coefficient of determination (R^2) for each model are given in Table A.1. P-values less than 0.05, indicating highly significant variables, are shown in bold type.

The results in Table A.1 show that IRI tends to be significantly affected by age, traffic, and environmental factors. The signs of the estimated coefficients indicate that the greater the Age, AADT, and Average Annual Wet Days, the higher the IRI. These trends are expected. High temperature days, on the other hand, seem to reduce IRI. This may be due to higher temperatures making it easier to obtain smoothness at the time of construction or some initial compaction of the mixes by trafficking after construction. Table A.1 also shows that rubberized binder tends to reduce IRI. The results of the analysis suggest that there is a strong correlation between the age of the pavement and the Average Annual Wet Days. MPD also explains some of the change in IRI. This is probably due to the variability of the raveling in the severely raveled sections with resultant holes in the mix causing the roughness. Sections that include asphalt rubber asphalt had lower IRI values compared to those with conventional asphalt.

Based on the results shown in Table A.1, multiple regression analysis was conducted to account for the effects of the various factors simultaneously. First a pair-wise correlation analysis was performed to avoid including highly correlated variables in the same model. It was found that air-void content and MPD are highly correlated. MPD is also partly determined by the maximum aggregate size in the mix because larger stones increase texture. Also, Average Annual Maximum Daily Air Temperature is highly correlated with Annual Number of Days >30°C and Annual Degree-Days >30°C. In the multiple regression analysis, only one variable in each highly correlated variable pair was considered.

Preliminary analysis revealed that the error terms from multiple regression have non-constant variance, so a reciprocal square-root transformation ($Y' = (\sqrt{IRI})^{-1}$) was applied to the dependent variable, IRI, to stabilize the variance of the error terms.

Because mix properties are highly affected by mix type (e.g., higher air-void contents in open-graded mixes than in dense- and gap-graded mixes), it was not appropriate to incorporate both mix property variables (e.g., air-void content) and mix type in the same model. To determine the effects of mix type and mix properties on IRI, separate regression models were proposed.

Table A.1: Regression Analysis of Single-Variable Models for IRI

	Variable	Coefficient	P-value	Constant Term	R-squared
1	**Age(years)**	**9.75E-02**	**4.62E-14**	1.016707	**0.190302**
2	Air-void Content (%)	-1.64E-02	1.96E-01	1.748137	0.01176
3	**Mix Type**	**-3.59E-01**	**2.93E-03**	1.917608	**0.086738**
4	**Rubber Inclusion**	**-2.50E-01**	**2.89E-03**	1.707047	**0.032403**
5	**MPD(microns)**	**2.11E-04**	**3.45E-02**	1.339317	**0.017213**
6	**Average Annual Rainfall(mm)**	**1.87E-04**	4.60E-02	1.467358	**0.014667**
7	Age*Average Annual Rainfall(mm)	4.22E-02	5.87E-02	1.066582	0.252643
8	**Average Annual Wet Days**	**2.18E-03**	**1.87E-02**	1.422194	**0.020316**
9	**Age*Average Annual Wet Days**	**6.86E-02**	**1.21E-02**	0.933957	**0.22843**
10	**Average Annual Maximum Daily Air Temp (C)**	**-9.05E-02**	**1.53E-08**	3.676601	**0.112014**
11	**Annual Number of Days > 30°C**	**-4.02E-03**	**2.46E-07**	1.898952	**0.094093**
12	**Annual Degree-Days > 30°C**	**-1.14E-04**	**1.77E-07**	1.892612	**0.096235**
13	Annual FT Cycles	-6.24E-03	6.26E-02	1.659602	0.012778
14	**AADT**	**1.37E-06**	**4.24E-02**	1.497295	**0.015162**
15	**Rainfall category**	**-3.13E-01**	**2.46E-04**	1.765998	**0.048653**
16	**Traffic Category**	**-2.70E-01**	**1.34E-03**	1.724539	**0.037449**
17	**Annual ESALs per Coring Lane**	**-1.19E-07**	**2.14E-02**	1.638965	**0.01946**

In the first model, only the mix type (categorical variable) and environmental and traffic factors were included as independent variables, while the mix property variables were excluded. The regression equation, Equation A.2.1, is

$$\begin{aligned}1/\sqrt{IRI}\,(m/km) &= 0.8738 - 0.021\times Age(year) + 0.07140\times ind\,(MixTypeOGAC) + 0.02180\times ind\,(MixTypeRAC-G)\\ &+0.11330\times ind\,(MixTypeRAC-O) - 0.0001\times AverageAnnualRainfall(mm) + 0.00060\times NumberOfDays > 30C\\ &+0.0023\times AnnualFTCycles\end{aligned} \quad \textbf{(A.2.1)}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if it is false. The coefficient of the $ind(\cdot)$ function represents the difference in the effects of the other mix types and DGAC. The estimated values and P-values of the parameters are shown below, with variables that are significant at the 95 percent confidence interval shown in bold type.

Table A.2: Regression Analysis of Multiple-Variable Models for IRI for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	**0.8766**	**0.0333**	**26.3541**	**0**
Age	**-0.0219**	**0.0025**	**-8.6458**	**0**
PvmntTypeOGAC	**0.0677**	**0.022**	**3.0735**	**0.0023**
PvmntTypeRAC-G	0.0199	0.0231	0.8637	0.3885
PvmntTypeRAC-O	**0.1144**	**0.0215**	**5.3164**	**0**
AvgAnnualRainfall	**-0.0001**	**0**	**-2.9152**	**0.0039**
NoDaysTempGT30	**0.0006**	**0.0002**	**3.6676**	**0.0003**
AADTTCoringLane	0	0	-1.6947	0.0913
AnnualFTCycles	**0.0022**	**0.0007**	**3.2655**	**0.0012**

Residual standard error: 0.1192 on 263 degrees of freedom; Multiple R-Squared: 0.40.

Although this model with the pooled data for all four mix types shows a slight improvement in terms of R^2, with a value of 0.40 compared to 0.38 in the fifth-year report, it does not do a very good job of predicting IRI. At the 95 percent confidence level, age, mix type, average annual rainfall, number of days greater than 30°C, and annual freeze-thaw cycles significantly affect IRI. The IRI increases with age and average annual rainfall, but decreases with the number of days greater than 30°C and annual freeze-thaw cycles. Interestingly, the effect of AADT in the coring lane was found to not be significant. Among the three pavement types, OGAC, RAC-G, and RAC-O, all had lower IRI than DGAC over the full data set, but only OGAC and RAC-O were statistically significantly different from DGAC.

In the second model, the mix type variable was replaced with variables defining the mix and the model was estimated for each mix type separately. The regression equations, Equation A.2.2 through Equation A.2.5, are shown below.

<u>For DGAC pavements:</u>

$$\begin{aligned} &1/\sqrt{IRI}\,(m/km) = 0.8953 - 0.0165 \times Age(year) - 0.0004 \times MPD - 0.0254 \times \log(Permeability)(cm/\sec) \\ &-0.0001 \times AverageAnnualRainfall(mm) + 0.0002 \times NumberOfDays > 30C \\ &+0.0025 \times AnnualFTCycles \end{aligned} \qquad \textbf{(A.2.2)}$$

Table A.3: Regression Analysis of Multiple-Variable Models for IRI for DGAC

	Value	Std. Error	P-value
(Intercept)	**0.8953**	**0.1425**	**0**
Age	**-0.0165**	**0.008**	**0.05**
MPD	**-0.0004**	**0.0002**	**0.0396**
logPerm	-0.0254	0.0158	0.1257
AvgAnnualRainfall	-0.0001	0	0.2181
NoDaysTempGT30	0.0002	0.0005	0.6561
AADTTCoringLane	0	0	0.3653
AnnualFTCycles	0.0025	0.0023	0.2934

Residual standard error: 0.1018 on 18 degrees of freedom; Multiple R-Squared: 0.70.

For OGAC pavements:

$$1/\sqrt{IRI}\,(m/km) = 0.7253 - 0.0062\times Age(year) - 0.0001\times MPD\,(micron) - 0.0215\times \log(Permeability)(cm/\sec) + 0.0009\times NumberOfDays > 30C + 0.0039\times AnnualFTCycles \qquad \textbf{(A.2.3)}$$

Table A.4: Regression Analysis of Multiple-Variable Models for IRI for OGAC

	Value	Std. Error	P-value
(Intercept)	**0.7253**	**0.1591**	**0.0001**
Age	-0.0062	0.0158	0.6984
MPD	-0.0001	0.0001	0.2767
logPerm	-0.0215	0.0179	0.2409
AvgAnnualRainfall	0	0.0002	0.8194
NoDaysTempGT30	0.0009	0.0006	0.169
AADTTCoringLane	0	0	0.4417
AnnualFTCycles	0.0039	0.0024	0.1125

Residual standard error: 0.1217 on 27 degrees of freedom; Multiple R-Squared: 0.41.

For RAC-G pavements:

$$\begin{aligned}1/\sqrt{IRI}\,(m/km) &= 1.1305 - 0.0099\times Age(year) - 0.0003\times MPD(micron) - 0.0161\times \log(Permeability)(cm/\sec)\\ &-0.0001\times AverageAnnualRainfall(mm) + .0007\times NumberOfDays > 30C\\ &-0.0001\times AADTTinCoringLane\end{aligned} \qquad \textbf{(A.2.4)}$$

Table A.5: Regression Analysis of Multiple-Variable Models for IRI for RAC-G

	Value	Std. Error	P-value
(Intercept)	1.1305	0.0898	0
Age	-0.0099	0.0103	0.3469
MPD	**-0.0003**	**0.0001**	**0.0017**
logPerm	-0.0161	0.0118	0.1872
AvgAnnualRainfall	-0.0001	0.0001	0.1662
NoDaysTempGT30	0.0007	0.0004	0.1137
AADTTCoringLane	**-0.0001**	**0**	**0.0099**
AnnualFTCycles	0	0.002	0.9858

Residual standard error: 0.0849 on 24 degrees of freedom; Multiple R-Squared: 0.68.

For RAC-O pavements:

$$1/\sqrt{IRI}\,(m/km) = 0.7984 - 0.0364\times Age(year) + 0.0001\times MPD(micron) - 0.0166\times \log(Permeability)(cm/\sec) + 0.0008\times NumberOfDays > 30C + 0.0021\times AnnualFTCycles \qquad \textbf{(A.2.5)}$$

Table A.6: Regression Analysis of Multiple-Variable Models for IRI for RAC-O

	Value	Std. Error	P-value
(Intercept)	**0.7984**	**0.1985**	**0.0003**
Age	**-0.0364**	**0.0101**	**0.0009**
MPD	0.0001	0.0001	0.361
logPerm	-0.0166	0.0224	0.4641
AvgAnnualRainfall	0	0.0001	0.9008
NoDaysTempGT30	0.0008	0.0006	0.2174
AADTTCoringLane	0	0	0.4576
AnnualFTCycles	0.0021	0.002	0.3104

Residual standard error: 0.134 on 37 degrees of freedom; Multiple R-Squared: 0.40.

The IRI models for DGAC and RAC-G have R^2 above 0.65, while the OGAC and RAC-O models have R^2 below 0.48. This is probably due to the interaction of several variables or nonlinearity inherent in the performance of the open-graded mixes. Also, for the OGAC mixes, for unknown reasons the middle group of initial ages (4 to 8 years old at the start of the study) were much smoother than the newly paved sections. For dense-graded mixes (DGAC and RAC-G), MPD was a significant variable at the 95 percent confidence level and increased the IRI of the mix, whereas the smoothness of open-graded mixes was not a function of the MPD. IRI increased with age for all mixes but this factor was not significant for the RAC-G and OGAC mixes. Traffic volume is a significant variable for RAC-G pavements and higher traffic volume led to a higher IRI. Table A.7 shows the summary statistics over the six years of data collection.

Table A.7: IRI (m/km) Summary Statistics Over the Six Years of Data Collection

		N	Range	Minimum	Mean	Maximum	Std. Deviation
DGAC	1.0	15.0	2.9	1.0	1.8	3.8	.9
	2.0	13.0	5.4	1.0	2.2	6.4	1.5
	3.0	12.0	3.4	1.0	1.9	4.4	1.0
	4.0	7.0	1.9	1.1	1.7	3.0	.7
	5.0	7.0	1.9	1.1	1.6	3.0	.7
	6.0	5.0	2.0	1.3	2.0	3.3	.9
OGAC	1.0	15.0	2.3	.7	1.5	3.0	.6
	2.0	17.0	2.7	.9	1.7	3.6	.7
	3.0	17.0	1.9	.8	1.6	2.7	.5
	4.0	17.0	2.1	.9	1.7	3.0	.6
	5.0	17.0	3.8	1.0	1.8	4.7	.9
	6.0	11.0	1.5	1.2	1.7	2.7	.5
RAC-G	1.0	13.0	1.8	.8	1.5	2.7	.5
	2.0	13.0	2.0	.9	1.6	2.9	.6
	3.0	10.0	1.9	1.0	1.7	2.9	.6
	4.0	10.0	1.8	1.0	1.6	2.8	.5
	5.0	9.0	1.8	1.3	1.7	3.1	.5
	6.0	4.0	.5	1.8	2.0	2.3	.2
RAC-O	1.0	19.0	2.0	.7	1.3	2.7	.5
	2.0	18.0	2.0	.8	1.3	2.8	.5
	3.0	17.0	2.2	.7	1.3	2.9	.6
	4.0	17.0	2.3	.7	1.4	3.1	.6
	5.0	17.0	2.5	.8	1.5	3.3	.6
	6.0	9.0	1.3	1.0	1.3	2.3	.4

A.2.3: Summary of Findings

The following findings were obtained regarding roughness:

1. The IRI models for DGAC and RAC-G have R^2 above 0.65, while the OGAC and RAC-O models have R^2 of about 0.4. This indicates that the roughness performance of the open-graded mixes was not explained well by the variables included in this study. Part of this may be due to differences in initial construction smoothness, which was not controlled in terms of IRI as part of the construction quality assurance process.

2. Except for one DGAC section, throughout the study all sections were smoother than the old Caltrans Pavement Management System (PMS) IRI trigger criterion of 3.6 m/km (224 in./mi). After the six years of the study, less than about 35 percent of the observations made on the DGAC test sections that were more than four years old at the start of the study showed IRI levels higher than the current PMS IRI trigger of 2.7 m/km (170 in./mi), and less than about 20 percent of the other mix types of similar age at the beginning of the study reached that level of roughness. This indicates that Caltrans generally treats pavements before they reach that IRI trigger.
3. Rubberized open-graded mixes had lower initial IRI values than non-rubberized open-graded mixes; non-rubberized dense-graded mixes had lower initial IRI values than rubberized gap-graded mixes.
4. The surface types OGAC, RAC-G, and RAC-O all had lower IRI than DGAC over the full data set, but only OGAC and RAC-O were statistically significantly different from DGAC. Monitoring over six years indicates that IRI increases with age on all mix types, but that the statistical significance of age varies. Specifically, age is statistically significant at a 5 percent level in increasing IRI on DGAC and RAC-O, but it was not significant on a level that high on OGAC and RAC-G.
5. Open-graded pavements (OGAC and RAC-O) were smoother in high temperature regions than in low temperature regions.
6. The IRI of dense- and gap-graded pavements was correlated with increasing MPD, whereas there was little correlation of MPD with IRI on open-graded mixes. The monitoring performed to date shows that traffic volume significantly affects IRI only on RAC-G pavements, with higher truck traffic volumes showing greater IRI values.

A.3: Surface Profile Analysis: Mean Profile Depth

The analysis of MPD answers these questions:

- What pavement characteristics affect MPD?
    - Are initial MPD and change in MPD with time different for rubberized and non-rubberized mixes?
    - Are initial MPD and MPD progression different for open-graded and dense-graded mixes?
- How do traffic and climate affect MPD?

Hypotheses regarding the effects of the explanatory variables on MPD are discussed in Reference *(1)*.

A.3.1: Descriptive Analysis

Figure 3.1 shows the average MPD measured over six consecutive years for the individual pavement sections of each of the four mix types: DGAC, OGAC, RAC-G, and RAC-O. In general, the MPD values increased with an increase in age, but the differences were small. The rate of MPD increase for most of the mix types was similar for all sections of that type and remained fairly constant throughout the service life for each section.

Figure A.5 shows the distribution of MPD values for the different mix types based on the six years of survey data. The information conveyed in the plot is similar to that in the plot based on the first five years of survey data *(3, 6)*. The RAC-G mixes had higher MPD values than the DGAC mixes, while the OGAC mixes had the highest MPD values of all the mixes. Of the two types of mixes with rubberized binders, the RAC-O mixes had higher MPD values than the RAC-G mixes, which is as expected based on their aggregate gradations. Higher macrotexture, as measured by MPD, is the most important factor in maintaining tire-pavement contact under wet conditions at high speeds.

Figure A.6 shows the trends in MPD over the six years for the different mix types broken down into the three initial age categories and survey year. It can be seen in the figure that OGAC sections in the middle initial age category (1 to 4 years) generally had lower MPD than those that were newly paved at the start of the study. It can also be seen that the newly paved RAC-G mixes began with a high MPD that decreased with time. DGAC had the lowest initial MPD values, which increased with time. RAC-O MPD values were initially similar to those of the OGAC and RAC-G and showed a trend of slowly increasing with time. This was shown in the earlier reports to be related to the poor compaction of the RAC-G mixes at the time of construction and to additional compaction under traffic. Table A.8 shows the summary statistics for MPD values over the six years of data collection. *(Note:* MPD is typically reported in either mm or microns [10^{-6} m]. Microns were used consistently in this study).

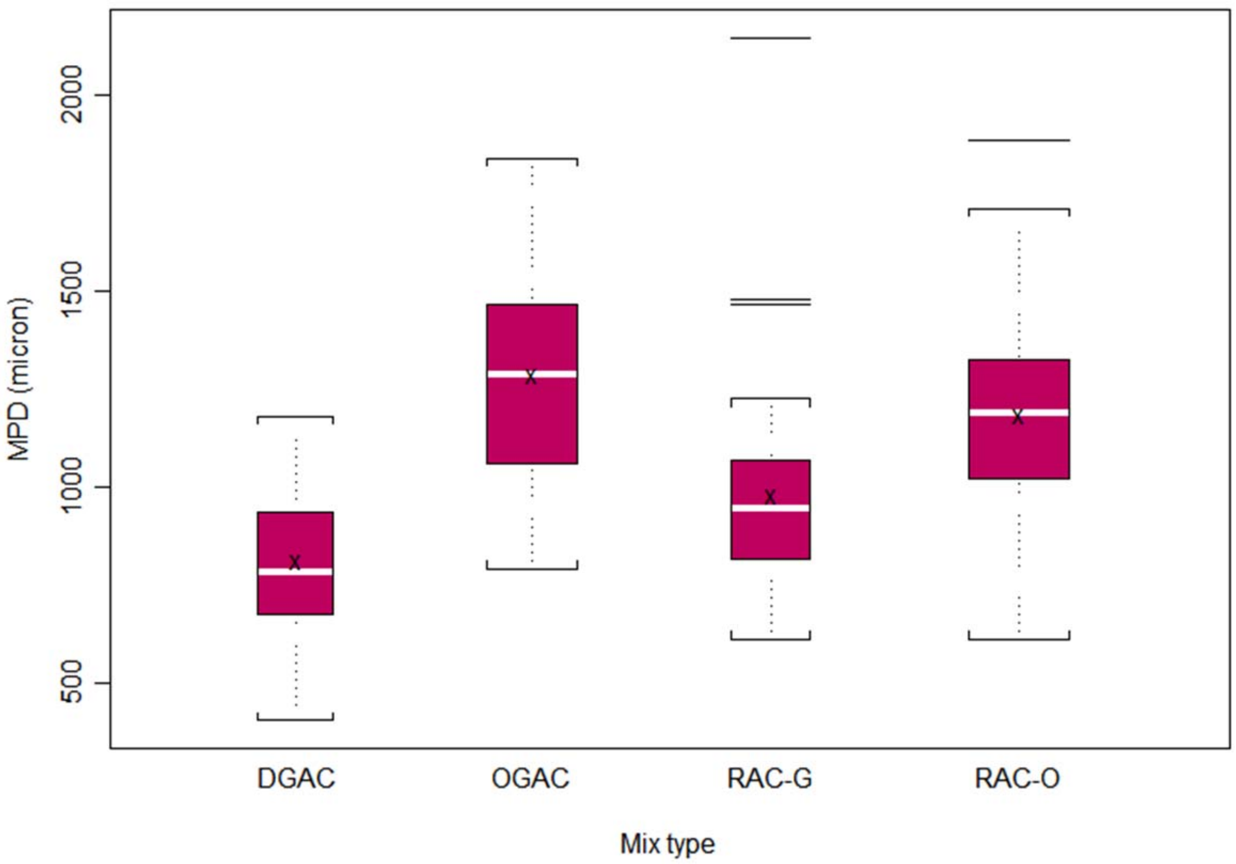


Figure A.5: Distribution of MPD values of the different mix types for all six years of pooled data and all initial ages.

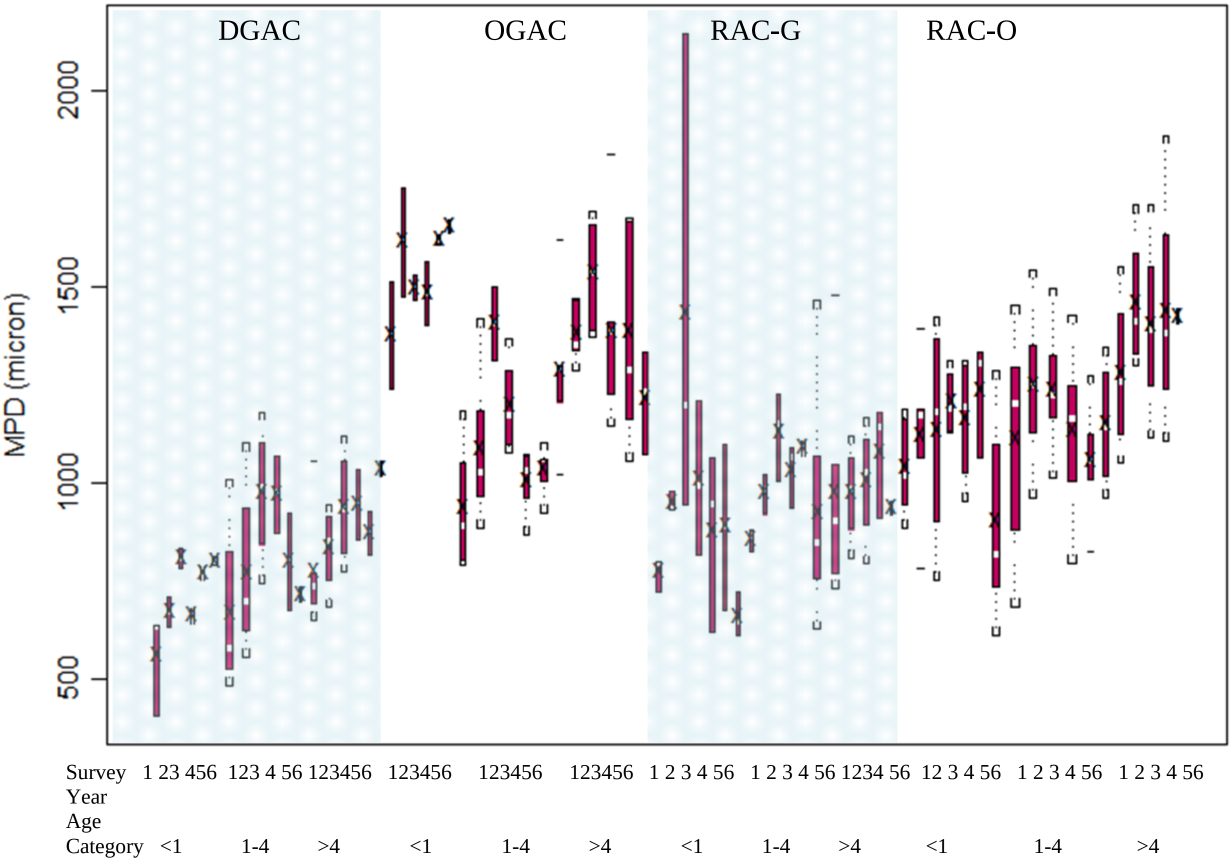


Figure A.6: Distribution of MPD values of the different mix types and different initial age categories (Age Category) across the six years of data collection.

Table A.8: MPD (microns) Summary Statistics over the Six Years of Data Collection

			Phase					
			1	**2**	**3**	**4**	**5**	**6**
Mix Type	DGAC	Valid N	16	12	11	7	7	5
		Mean	692	775	900	839	764	796
		Standard Deviation	174	163	170	234	160	153
		Minimum	406	558	629	408	463	625
		Maximum	1,059	1,103	1,181	1,070	928	1,037
		Range	653	545	552	662	465	411
	OGAC	Valid N	15	15	13	17	17	12
		Mean	1,158	1,322	1,536	1,347	1,531	1,399
		Standard Deviation	247	258	144	204	802	817
		Minimum	794	887	1,315	1,076	870	926
		Maximum	1,623	1,752	1,828	1,839	3,810	3,916
		Range	829	865	512	762	2,940	2,990
	RAC-G	Valid N	13	12	10	10	9	4
		Mean	830	938	1,112	1,042	996	951
		Standard Deviation	227	194	379	152	168	196
		Minimum	615	734	810	796	621	679
		Maximum	1,466	1,480	2,148	1,227	1,181	1,098
		Range	852	746	1,338	430	560	420
	RAC-O	Valid N	17	17	15	17	17	9
		Mean	1,001	1,154	1,274	1,269	1,213	1,052
		Standard Deviation	215	239	237	168	253	399
		Minimum	614	686	755	1,012	798	113
		Maximum	1,347	1,553	1,710	1,712	1,888	1,425
		Range	733	867	955	700	1,089	1,312

A.3.2: Regression Analysis

Regression analysis was performed to evaluate the effects of traffic, climate, and pavement materials on MPD values. First, a single-variable regression analysis was conducted to prescreen the significant factors to be included in a multiple regression model. Estimates of the coefficient of the explanatory variable and the constant term along with their P-values and the coefficient of determination (R^2) for each model are given in Table A.9. P-values less than 0.05 are shown in bold type. Descriptions of the variables are provided in References *(1, 3)*.

Table A.9: Regression Analysis of Single-Variable Models for MPD

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	**Age(years)**	**26.55**	**2.79E-06**	**908.52**	**0.08**
2	**Air-void Content (%)**	**37.75**	**0.00E+00**	**572.44**	**0.44**
3	**Mix Type**	**436.53**	**0.00E+00**	**784.25**	**0.34**
4	**Rubber Inclusion**	**80.88**	**2.30E-02**	**1016.60**	**0.02**
5	**Fineness Modulus**	**364.73**	**0.00E+00**	**-744.08**	**0.32**
6	**NMAS (mm)**	**-38.47**	**4.00E-07**	**1552.27**	**0.09**
7	**Cu**	**-9.89**	**0.00E+00**	**1273.60**	**0.28**
8	Cc	7.41	4.18E-01	1044.76	0.00
9	**Surface Thickness (mm)**	**-5.92**	**1.37E-10**	**1301.60**	**0.14**
10	IRI(m/km)	54.65	5.83E-02	975.54	0.01
11	Average Annual Rainfall(mm)	0.01	7.29E-01	1052.19	0.00
12	Average Annual Wet Days	0.57	1.33E-01	1019.33	0.01
13	Average Annual Maximum Daily Air Temp (C)	-3.21	6.48E-01	1134.21	0.00
14	Annual Number of Days > 30C	-0.64	6.62E-02	1110.66	0.01
15	Annual Degree-Days > 30C	-0.02	7.66E-02	1107.22	0.01
16	Annual FT Cycles	0.21	8.76E-01	1056.99	0.00
17	Annual AADTT per Coring Lane	0.01	3.60E-01	1047.22	0.00

The results in Table A.9 show that MPD tends to be significantly affected by the age and mix property variables, including air-void content, fineness modulus (a parameter describing the openness of the aggregate gradation), nominal maximum aggregate size (NMAS), aggregate coefficient of uniformity (C_u, another parameter describing the openness of the aggregate gradation), rubber inclusion, and surface layer thickness. Increasing air-void content and fineness modulus increase macrotexture, and increasing NMAS and C_u reduce macrotexture. A decrease of macrotexture with an increase of NMAS is unexpected since larger aggregates tend to have a higher macrotexture. This is likely due to the pooling of dense- and open-graded mixes and the effects of other uncontrolled factors in the single-variable model. Also, macrotexture tends to be smaller on thicker surface layers; this is probably due to the better compaction applied to thicker layers to produce a smoother surface. The variable for rubberized mixes (rubber inclusion) shows higher MPD values because the gap- and open-gradations of the rubberized mixes provide a rougher surface while the non-rubberized mix category included a dense gradation. As was observed in the earlier reports, higher temperature (in terms of both maximum daily air temperature and the number of days with air temperature greater than 30°C) tends to reduce macrotexture. The effect of air temperature, however, is not statistically significant. Pavements with heavier daily traffic volume tend to have higher macrotexture, which is most likely due to the removal of fines around the larger stones in the surface, which results in accelerated raveling. The effect of traffic is also not statistically significant. Among all of the variables, air-void content, gradation, and mix type explain most of the differences observed among the different mixes.

Multiple regression analysis was conducted to account for the effect of various factors simultaneously. Highly correlated independent variables were mutually excluded from the modeling and the variables with the highest explanatory value were considered in the model. One model was created with all mixes included and mix type as a variable, and a second regression was performed for each mix type with the mix variables included. The effects of traffic and temperature were considered in the analysis to account for any interaction between mix type and temperature that may have led to the finding of an insignificant effect for these two factors.

In the first model, only the mix type (categorical variable), and environmental and traffic factors were included as the independent variables, while mix property variables were excluded. The regression equation, Equation A.3.1, is

$$\begin{aligned}
&MPD(micron) = 936.7149 + 13.7345 \times Age(year) + 210.732 \times ind(MixTypeOGAC) + 199.0727 \times ind(MixTypeRAC - G) \\
&+291.8019 \times ind(MixTypeRAC - O) - 9.0708 \times NMAS(mm) - 0.913 \times Thickness(mm) - 0.7364 \times NumberOfDays > 30C \\
&+0.0036 \times AADTTinCoringLane + 26.1576 \times Age \times ind(MixTypeOGAC) - 3.6095 \times Age \times ind(MixTypeRAC - G) \\
&+11.9101 \times Age \times ind(MixTypeRAC - O)
\end{aligned} \quad \textbf{(A.3.1)}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if it is false. The estimated values and P-values of the parameters are shown below.

Table A.10: Regression Analysis of Multiple-Variable Models for MPD for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	936.7149	139.0467	6.7367	0
Age	13.7345	8.4061	1.6339	0.1035
PvmntTypeOGAC	210.732	116.0952	1.8152	0.0707
PvmntTypeRAC-G	**199.0727**	**83.9317**	**2.3718**	**0.0184**
PvmntTypeRAC-O	**291.8019**	**80.0503**	**3.6452**	**0.0003**
NMAS	-9.0708	7.1827	-1.2629	0.2078
Thickness	-0.913	0.939	-0.9723	0.3318
NoDaysTempGT30	**-0.7364**	**0.2868**	**-2.5671**	**0.0108**
AADTTCoringLane	0.0036	0.0093	0.3894	0.6973
AgePvmntTypeOGAC	26.1576	16.1742	1.6172	0.1071
AgePvmntTypeRAC-G	-3.6095	13.0673	-0.2762	0.7826
AgePvmntTypeRAC-O	11.9101	11.563	1.03	0.304

Residual standard error: 223.9 on 255 degrees of freedom; Multiple R-Squared: 0.43.

The R^2 value is a relatively low 0.43 but it indicates some ability of the combined mix type model to explain MPD. It can be seen that at the 95 percent confidence level, the number of days during which temperature is greater than 30°C and the mix type significantly affect macrotexture. The pavement types OGAC, RAC-G, and RAC-O all had higher MPD than DGAC over the set of observations in the study, but OGAC was statistically insignificantly different from DGAC. P-values for the interaction terms between age and mix type indicate that the growth rate (with age) of MPD for the OGAC and RAC-O mixes was higher than that of the DGAC pavements. The MPD growth rate of the RAC-G mix decreased with time, reflecting the nonlinear trend in MPD for this mix type, with its high initial MPD that was followed by a reduction under traffic, which was then increased again later. However, none of these differences is statistically significant.

In the second model, the mix type variable was replaced with mix property variables and the model was estimated for each mix type separately. The regression equations, Equation A.3.2 through Equation A.3.5, are:

For DGAC pavements:

$$\begin{aligned}&MPD(micron) = -330.3525 - 3.0386 \times AirVoid(\%) + 21.4366 \times Age(year) + 363.1116 \times FinenessModulus\\&-26.4093 \times NMAS(mm) - 3.0755 \times Thickness(mm) - 0.0558 \times NumberOfDays > 30C\\&-0.0174 \times AADTTinCoringLane\end{aligned} \tag{A.3.2}$$

Table A.11: Regression Analysis of Multiple-Variable Models for MPD for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	-330.3525	537.8559	-0.6142	0.5464
AirVoid	-3.0386	20.4435	-0.1486	0.8834
Age	**21.4366**	**8.4419**	**2.5393**	**0.02**
FinenessModulus	**363.1116**	**159.9047**	**2.2708**	**0.035**
NMAS	**-26.4093**	**11.392**	**-2.3182**	**0.0317**
Thickness	-3.0755	1.7611	-1.7463	0.0969
NoDaysTempGT30	-0.0558	0.6373	-0.0876	0.9311
AADTTCoringLane	-0.0174	0.0177	-0.9857	0.3367

Residual standard error: 127.3 on 19 degrees of freedom; Multiple R-Squared: 0.611.

For OGAC pavements:

$$\begin{aligned}&MPD(micron) = -550.1207 + 24.184 \times AirVoid(\%) + 49.0285 \times Age(year) - 68.4283 \times FinenessModulus\\&+32.2988 \times NMAS(mm) + 0.352 \times Thickness(mm) - 0.3292 \times NumberOfDays > 30C\\&-0.0095 \times AADTTinCoringLane\end{aligned} \tag{A.3.3}$$

Table A.12: Regression Analysis of Multiple-Variable Models for MPD for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	550.1207	679.1652	0.81	0.4259
AirVoid	24.184	18.9477	1.2764	0.214
Age	**49.0285**	**15.1733**	**3.2312**	**0.0036**
FinenessModulus	-68.4283	169.4256	-0.4039	0.6899
NMAS	32.2988	30.3936	1.0627	0.2985
Thickness	0.352	2.6739	0.1316	0.8964
NoDaysTempGT30	-0.3292	0.6469	-0.5088	0.6155
AADTTCoringLane	-0.0095	0.0391	-0.2425	0.8105

Residual standard error: 144.8 on 24 degrees of freedom; Multiple R-Squared: 0.644.

For RAC-G pavements:

$$MPD(micron) = -872.4887 + 5.2345 \times AirVoid(\%) + 43.0568 \times Age(year) + 344.434 \times FinenessModulus$$
$$-22.8804 \times NMAS(mm) + 0.6661 \times Thickness(mm) + 1.8153 \times NumberOfDays > 30C \quad \textbf{(A.3.4)}$$
$$-0.0398 \times AADTTinCoringLane$$

Table A.13: Regression Analysis of Multiple-Variable Models for MPD for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	-872.4887	1415.911	-0.6162	0.5447
AirVoid	5.2345	28.7775	0.1819	0.8575
Age	**43.0568**	**18.4155**	**2.3381**	**0.0299**
FinenessModulus	344.434	302.6988	1.1379	0.2686
NMAS	-22.8804	26.4745	-0.8642	0.3977
Thickness	0.6661	3.8977	0.1709	0.866
NoDaysTempGT30	1.8153	0.9959	1.8228	0.0833
AADTTCoringLane	-0.0398	0.0486	-0.8193	0.4223

Residual standard error: 211.1 on 20 degrees of freedom; Multiple R-Squared: 0.3099.

For RAC-O pavements:

$$MPD(micron) = 545.1431 + 3.3972 \times AirVoid(\%) + 19.2707 \times Age(year) + 380.1482 \times FinenessModulus$$
$$-134.8575 \times NMAS(mm) + 6.7599 \times Thickness(mm) - 0.8906 \times NumberOfDays > 30C \quad \textbf{(A.3.5)}$$
$$-0.0095 \times AADTTinCoringLane$$

Table A.14: Regression Analysis of Multiple-Variable Models for MPD for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	545.1431	814.5842	0.6692	0.5072
AirVoid	3.3972	13.2987	0.2555	0.7997
Age	**19.2707**	**8.4772**	**2.2732**	**0.0285**
FinenessModulus	**380.1482**	**183.5979**	**2.0705**	**0.0449**
NMAS	**-134.8575**	**27.9369**	**-4.8272**	**0**
Thickness	**6.7599**	**2.9901**	**2.2608**	**0.0293**
NoDaysTempGT30	-0.8906	0.5274	-1.6885	0.0991
AADTTCoringLane	-0.0095	0.0137	-0.6961	0.4904

Residual standard error: 143.7 on 40 degrees of freedom; Multiple R-Squared: 0.6799.

The R^2 for the RAC-G model is very low, showing that none of the considered variables can effectively define that variation of MPD and the nonlinear trend with respect to age. The RAC-G mixes show an initial decrease in MPD due to compaction followed by slow increases in macrotexture over their service life afterward, which indicates little tendency to ravel. The R^2 of the models for the other three mixes were all above 0.60. This indicates that the developed models do a good job in predicting the variation of MPD over service life. When all the mixes are compared, the OGAC mixes showed the greatest change in macrotexture over their service life, indicating that this type of mix has the greatest propensity to ravel over time. The results showed that within each mix type, air-void content did not have a significant effect on the value of MPD. Fineness modulus significantly affected the macrotexture of DGAC and RAC-O pavements but was insignificant for RAC-G and OGAC pavements. Generally, macrotexture increased with fineness modulus, with increasing fineness modulus indicating a coarser gradation. Layer thickness was significant on RAC-O pavements, with thicker layers having higher MPD most likely because of the larger aggregate sizes (NMAS) being used in the thicker layers. The effect of pavement age on macrotexture was statistically significant for all four mix types, and was more significant (in terms of practical significance) on nonrubberized open-graded pavements (OGAC) than on rubberized open-graded pavements (RAC-O). Table A.18 summarizes the significant factors for all mixes.

Table A.15: Summary of Significant Factors for All Mixes

	DGAC	OGAC	RAC-G	RAC-O
AirVoid				
Age	✓	✓	✓	✓
FinenessModulus	✓			✓
NMAS	✓			✓
Thickness				✓
NoDaysTempGT30			✓*	✓*
AADTTCoringLane				

Note:
* at 10 percent significance level

A.3.3: Summary of Findings

The following findings were obtained regarding macrotexture:

1. Among all the mixes investigated, OGAC had the highest MPD. The RAC-G mixes had higher MPD values than the dense-graded mixes, and the open-graded mixes had higher MPD values than the RAC-G mixes. Of the two open-graded mixes, the OGAC mixes had higher MPD values than the RAC-O mixes.

2. The R^2 for the RAC-G model is very low, because the RAC-G mixes show a non-linear trend versus age with higher initial MPD followed by a reduction under traffic and then a gradual increase later on, with the later gradual increase indicating little propensity to ravel. The R^2 of the models for the other three mixes are all above 0.60. The OGAC mixes showed the greatest change in macrotexture over their service lives, indicating that they have the highest propensity for raveling over time.
3. MPD generally increased with pavement age. For the open-graded mixes, the effect of age on macrotexture was more prominent on nonrubberized mixes (OGAC) than on rubberized mixes (RAC-O). The growth rate (with age) of MPD was significantly higher on OGAC pavements than on DGAC, RAC-G, and RAC-O pavements. The MPD growth rates of RAC-G and RAC-O pavements were not statistically different from those of DGAC pavements.
4. Within each mix type, air-void content did not have a significant effect on the value of MPD.
5. Fineness modulus significantly affected the macrotexture of dense-graded mixes, with coarser gradations having higher macrotexture, but was insignificant for the RAC-G and OGAC pavements.
6. Layer thickness was only significant on RAC-O pavements. Thicker RAC-O layers had higher macrotexture, which is likely due to the larger maximum aggregates sizes (NMAS) being used with the thicker layers.
7. The MPD of rubberized mixes was significantly affected by the number of days that the temperature is greater than 30°C at a significance level of 10 percent.

A.4: Sound Intensity Analysis

The On-board Sound Intensity (OBSI) results are given in terms of spectral content in one-third octave bands. OBSI was also measured in terms of overall A-weighted sound intensity levels. Analysis in this section first focuses on overall sound intensity and then on the one-third octave band noise levels in several typical frequency bands. Among the questions answered by this analysis are these:

- What is the trend with time for overall OBSI?
  - How do the mixes rank with respect to OBSI, initially and with time?
  - How is the change with time different for each mix type?
  - What variables affect OBSI for each mix type?
- What are the answers to the questions above for the different OBSI frequency ranges?

It is generally accepted that the tire vibration noise–generating mechanism is mostly responsible for low-frequency noise (800 Hz and below), and that the air-pumping mechanism is mostly responsible for high-frequency noise (2,000 Hz and higher frequencies). It is also generally accepted that the 800 Hz and 1,000 Hz frequencies are predominantly influenced by tire tread size, with some lesser influence from both of the pavement-related mechanisms (air pumping and tire vibration). The 800 Hz and 1,000 Hz frequencies also often have the highest sound intensity on the A-weighted scale due to the nature of tire/pavement noise mechanisms and the weighting for human perception. Therefore, variables that increase tire vibration, such as increased macrotexture, roughness, and NMAS, would generally be expected to increase low-frequency noise, while variables that mitigate the air-pumping mechanism, such as increased air-void contents, would be expected to decrease high-frequency noise. Overall noise levels are influenced by the combined effects of the different frequencies *(5).* The hypotheses regarding the effects of the explanatory variables on noise have been discussed in the analysis of the first three years of data *(1, 3),* but they are revisited in more detail in this report based on the combined six years of data.

A.4.1: Conversion of Sound Intensity for Temperature, Speed, Air Density, Equipment, and Tire

Sound intensity measurements may be affected by temperature, test car speed, test tire type, sound analyzer type, and air density.

The effect of pavement temperature was included as part of this study and has been addressed in a separate report *(5).* In the analysis of the first four years' results *(2, 3, 4)* the pavement temperature correction was not applied because calibration equations were unavailable at that time, and it was believed that the effect of pavement temperature on noise is small. The effect of pavement temperature was analyzed explicitly in the fourth year of the study *(5),* and it was verified that the pavement temperature correction is small (about -0.018 dB per increase of one degree Celsius for general asphalt pavements). For this reason, the pavement temperature correction was not used in the analysis of the six years of data discussed in this report.

In general, sound intensity measurements were conducted at a speed of 60 mph (96 km/h). However, due to constraints imposed by safety, road geometry, and traffic conditions, in some cases pavement sections were tested at either 30 mph (50 km/h) or 35 mph (56 km/h). In the analysis of the first three years of data, the 35 mph measurements were converted to the equivalent 60 mph measurements using an empirical equation, as described in the two-year noise study report *(1),* while the 30 mph measurements (on Sections QP-48 and QP-49) were discarded due to a lack of conversion equations. UCPRC and Caltrans agreed to remove both the 30 mph and 35 mph measurements from the analysis for this report.

In the analysis of the first two years of data, sound intensities measured with an Aquatred 3 tire were used *(1).* In the analysis of the three-year data, the first two-years' sound intensities were converted to equivalent Standard Reference Test Tire (SRTT) measurements using a set of correlation equations developed by simple linear regression analysis from both the Aquatred 3 #2 tire and the SRTT#1 tire (used late in the second year for that project) measurements on 24 QP pavement sections. These converted measurements were combined with the third-year SRTT#1 measurement for analysis in the third-year report *(3)*. In the fourth-year, data that were collected with the SRTT#2 tires were converted to SRTT#1 data using a set of newly developed correction equations described in Appendix B.2.

In this report, the sixth-year data, which were collected with the SRTT#5 tire, have been converted to SRTT#1 data by the same equation developed and presented in Appendix B.2.

In the fourth survey year, the Larson Davis real-time sound analyzer was replaced with a Harmonie sound analyzer, and this caused significant differences in the measured sound intensity levels. Before further analysis, however, the Larson Davis results were converted to equivalent Harmonie values so they could be compared with new data measured by Harmonie.

As discussed above, several varying factors were involved in the measurement of OBSI over the six years. A summary of the experiments and results is also included in Appendix B.2.

After all the sound intensity measurements were calibrated to their equivalent values at the reference condition (60 mph vehicle speed, Harmonie equipment, and SRTT#1), the same air-density correction equations as those used in the first three years were applied to the data to account for differences caused by variations in air density (a function of air temperature, humidity, and altitude) *(1)*.

A.4.2: Evaluation of Overall Sound Intensity

Overall A-weighted sound intensity levels are calculated by summing the sound intensity levels at each frequency using Equation (A.5.1):

$$\text{Overall OBSI (dBA)} = 10 \times \log \sum_i 10^{f_i/10} \qquad \textbf{(A.5.1)}$$

where f_i is the A-weighted sound intensity level at each one-third octave frequency, dBA. The frequencies included in the analysis in this study range between 500 Hz and 5,000 Hz. Although the above equation can be used to calculate the overall sum of the individual sound intensities measured at different frequencies, this method was not used in this project because it carries all of the problems of the conversions with it. Instead, the overall sum calculated by the noise analyzer software was used as the basis and then converted to SRTT#1.

A.4.2.1: Descriptive Analysis

It can be seen from Figure 4.2 and Figure 4.3 that the OBSI values in the sixth survey year were generally higher than those in the fifth survey year. Also, the OBSI time trends of the various surface mixes were the same as those observed in the fifth-year data analysis: the overall noise level generally increased with pavement age. For newly paved overlays at the start of the study, the overall sound intensities measured on the OGAC, RAC-G, and RAC-O pavements were lower than the values measured on the DGAC pavements. RAC-O had the lowest overall noise level. After the pavements were subjected to traffic, the overall sound intensity measured on newly paved RAC-G pavements and the RAC-G pavements that were one to four years old at the beginning of the study quickly approached those values measured for DGAC pavements of similar ages. This was previously found to be attributable to a large decrease in air-void content of the RAC-G mixes between construction and two years after construction that was due to generally poor compaction during construction *(1, 2)*. Figure A.7 shows the measured average overall OBSI versus age for OGAC and RAC-O pavements in the study, and Figure A.8 shows the estimated trends using a simple exponential function through the average values for both mixes. The initial noise levels appear to be similar for both mixes, however, the noise levels for OGAC mixes appear to increase more rapidly with age. With a few exceptions, the overall sound intensity measured on the RAC-O pavements appears to increase at a slower rate than OGAC for about ten years and then increase more rapidly with pavement age. Based on these observations, the rank of the four mix types (from best to worst) in terms of overall OBSI is RAC-O, OGAC, RAC-G, and DGAC, with OGAC and RAC-G generally having similar performance over time.

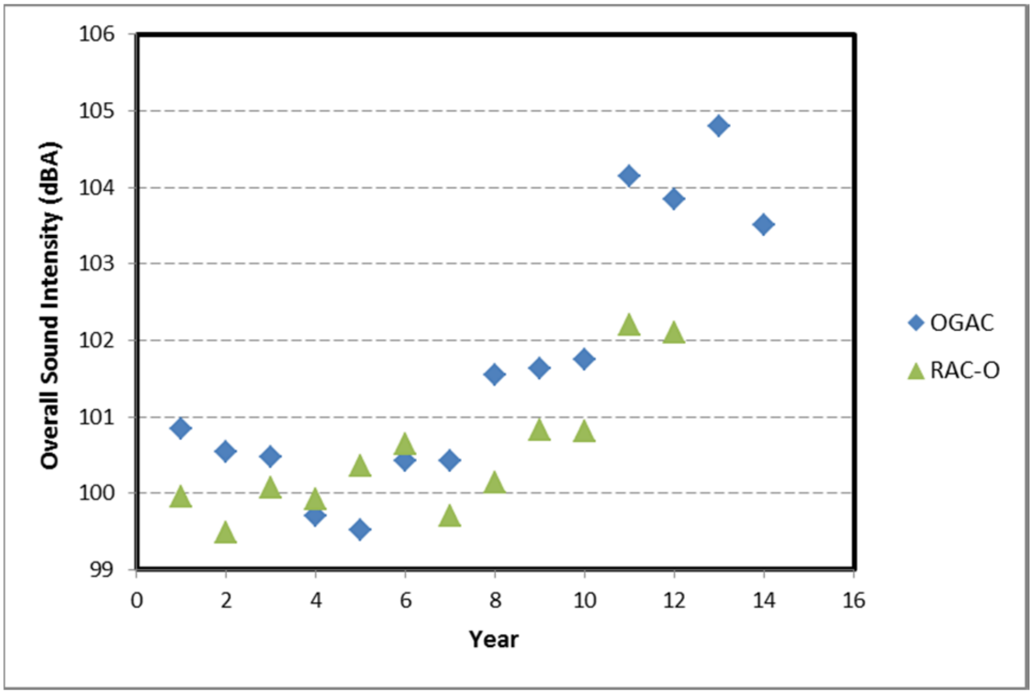
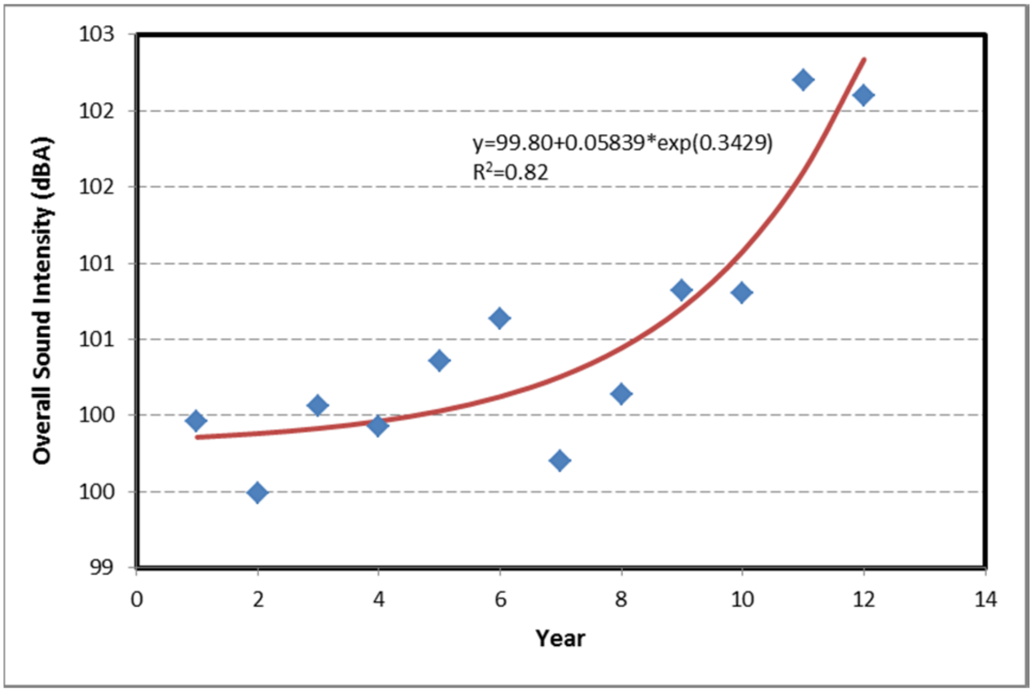
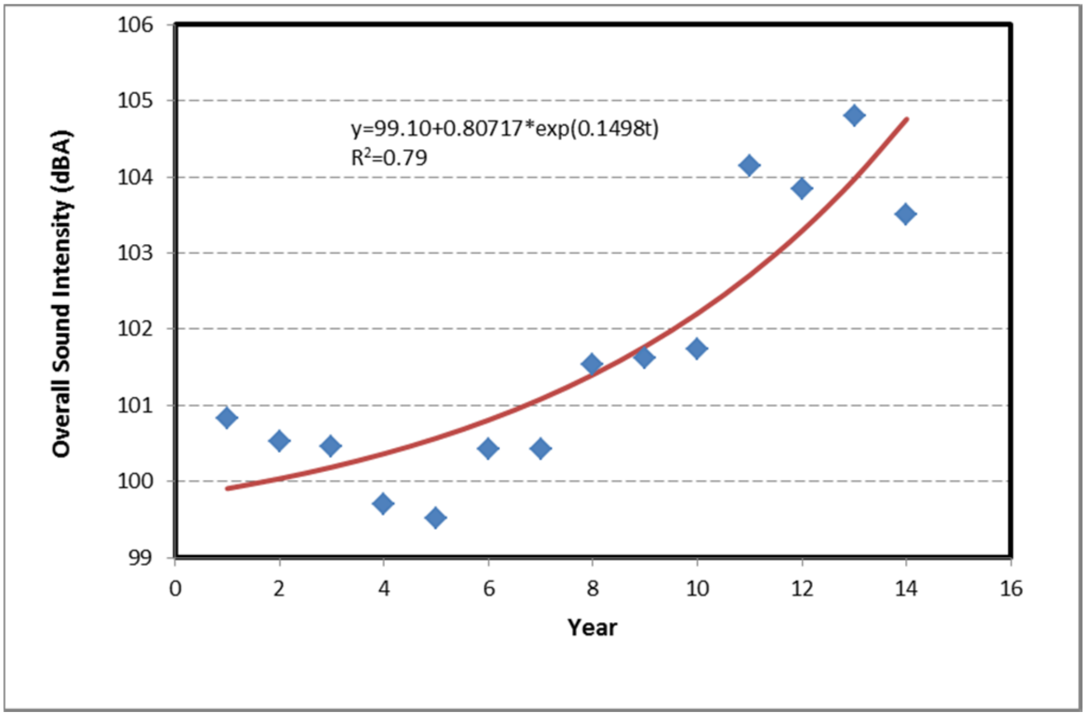


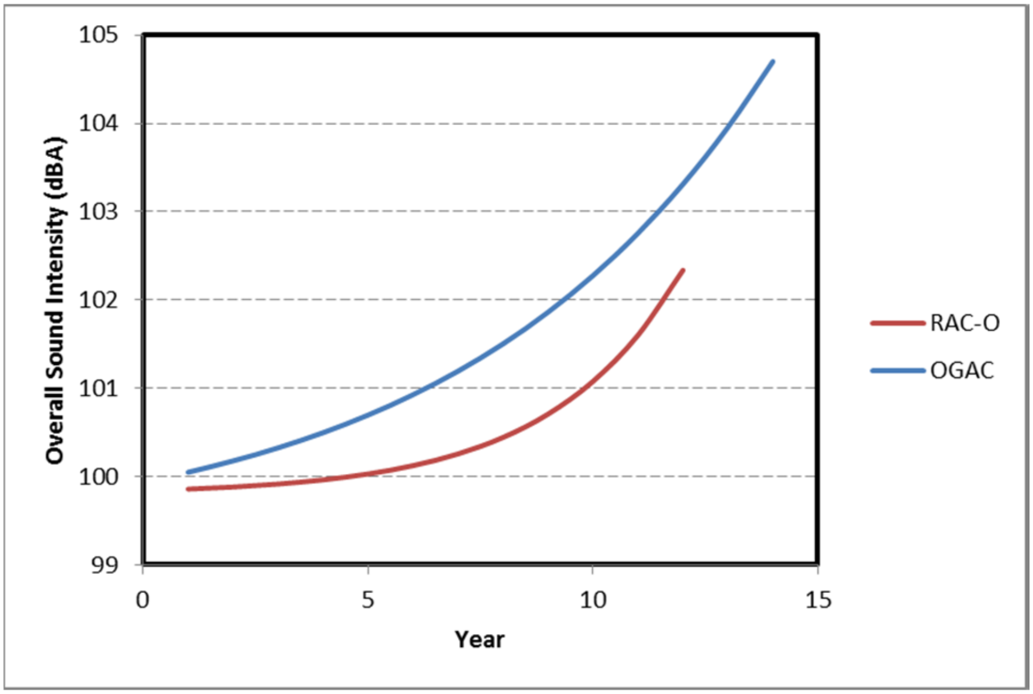
Figure A.7: Measured overall OBSI levels for OGAC and RAC-O mixes based on overage values for each age.



(a) RAC-O exponential trend for OBSI versus age for average values



(b) OGAC exponential trend for OBSI versus age for average values



(c) RAC-O and OGAC OBSI trend lines

Figure A.8: Estimated overall OBSI levels for RAC-O and OGAC mixes based on overage values for each age.

Figure 4.2 shows that there are a few pavement sections on which the measured sound intensity dropped significantly in later years of data collection. These sections are 01-N114 (DGAC), QP-20 (OGAC), 01-N105 (OGAC), QP-42 (RAC-O), QP-13 (OGAC), QP-32 (RAC-O), and 06-N466 (RAC-O).

The overall OBSI value measured on Section 01-N114 in the third survey year was about 2 dBA lower than the value measured in the second survey year. The reason for the drop is unclear. It is possibly due to the use of different test tires (Aquatred 3 tire in the second year versus SRTT in the third year, combined with of variations in pavement temperature (the measurement was taken in August in the second year and in May in the third year), and other random errors.

The overall OBSI value measured on Section QP-20 decreased with pavement age. As noted earlier, Section QP-20 is located on a steep hill and may have experienced compaction problems during construction. This section had high MPD to begin with, and the measured MPD increased in the third year, which would generally result in increased rather than decreased noise. Another possible explanation may be that the steep incline makes recording accurate OBSI data difficult because it is hard to maintain the required constant speed. The potential reasons for anomalous behavior in other sections have been discussed in more details in the three-year data analysis report *(3)*.

Figure 4.3 shows the box plots of overall OBSI over six years for different mix types for the three original age categories. As the figure shows, overall sound intensity generally increased with pavement age for the same pavement section. Overall, the rate of increase in sound intensity was lowest on the RAC-O pavements, which means that they remained quieter than DGAC pavements longer than did OGAC pavements.

As pointed out earlier and in previous reports *(3, 4, 5)*, for this study *quieter* and *noise reducing* (and *noise reduction*) have been defined as the difference between the average tire/pavement noise produced by OGAC, RAC-G, or RAC-O in a particular age category compared to the average noise level produced by of DGAC in that same age category. Figure A.9 shows the estimated cumulative distribution function (CDF) of noise reduction for both the OGAC and RAC-O types of open-graded mixes and the RAC-G mixes in terms of noise on those mixes compared to the average noise levels of the DGAC mixes in six age groups: less than or equal to one year, between one and three years, between three and five years, between five and seven years, between seven and nine years, and greater than nine years. The CDF curves were estimated using a kernel density estimation technique that smoothes the curves. The numbers in parentheses in the legends represent the sample size of each mix type. All six years of observations were aggregated to create the plots. As can be seen, the sample sizes differ among the different mixes and age groups.

A positive value in Figure A.9 indicates a reduction in noise levels compared to the average DGAC mix noise level. The figure shows that, with the exception of a few outliers, the range of noise on RAC-O, OGAC, and RAC-G compared to DGAC was generally between a 3 dBA increase and an 8 dBA reduction.

Among newly paved overlays (with ages less than or equal to one year), RAC-G and RAC-O pavements appear to be quieter than OGAC pavements with about 50 percent of the observations having 2 dBA or more noise reduction compared with DGAC, although this is based on results derived from small sample sizes. On the other hand, none of the OGAC pavements met the 2 dBA criterion. Almost none of the different mixes is more than 3 dBA quieter than DGAC pavements in the same newly paved age category. For newly paved DGAC overlays, the average tire/pavement noise level was approximately 101.3 dBA. The study results showed that average tire/pavement noise levels for newly paved overlays with RAC-G and with OGAC and RAC-O open-graded mixes were lower than those of the DGAC mixes by median values of approximately 0.1 dBA, 1.0 dBA, and 1.9 dBA, respectively.

For pavements with ages between one and three years, the OGAC and RAC-O pavements performed similarly: about 20 percent were at least 3 dBA quieter and 40 percent were at least 2 dBA quieter than average DGAC pavement, while only 10 percent of the RAC-G sections met the 3 dBA criterion in the same age category.

For pavements with ages between three and five years, the OGAC and RAC-O pavements showed similar noise-reducing abilities, while RAC-G pavements in this age category began to lose their noise-reducing properties. The DGAC pavements within this age category that were used as a reference become noisier with age (103.3 dBA in the three-to-five year age range versus 101.3 dBA at less than one year). About 30 percent of the RAC-O and OGAC pavements and only 5 percent of RAC-G pavements in this age range were at least 3 dBA quieter than the average DGAC pavement within the same age range.

For pavements with ages between five and seven years, the RAC-O pavements outperformed both the RAC-G and the OGAC pavements in terms of noise-reduction capabilities, with 60 percent of the RAC-O pavements 3 dBA or more quieter than the corresponding DGAC pavements. For pavements with ages between seven and nine years, RAC-O seemed to be the only option for consistently reducing noise levels by at least 3 dBA compared with DGAC of the same age range, with about 40 percent of the RAC-O mixes meeting that criteria and almost none of the OGAC and RAC-G mixes meeting it.

For pavements that are older than nine years, no mix type can be used to achieve the 3 dBA noise-reducing effect, although 60 percent of the RAC-O mixes were at least 2 dBA quieter than the DGAC average in the same age category. Interestingly, OGAC pavements with ages older than nine years old seem to be noisier than DGAC pavements, probably due to clogging and raveling.

A.4.2.2 Regression Analysis

Regression analysis was conducted to determine the effects of mix properties, traffic, and weather conditions on sound intensity levels, and to develop prediction models for tire/pavement noise. A single-variable regression analysis was first conducted to check the correlation between the dependent variable and each independent variable, and then a multiple regression model was estimated to consider the effects of various variables simultaneously.

Air-void content and permeability are important mix variables that affect tire/pavement noise, so they were included in the noise prediction models. Both variables were measured in the first two-year survey *(1)*, in the fourth year for about half of the sections, and in the sixth year for a small sample of pavements. No measurements for these variables were made in the third year and fifth years *(3, 6)*. Appendix B.3 shows the trend lines and box plots of the two variables. It can be observed that generally both air-void content and the logarithm of permeability decreased linearly with time for all mixes. Based on these observations, the missing third-year and fifth-year data were estimated by linear extrapolation or by simple linear regression from the available two-year and three-year data.

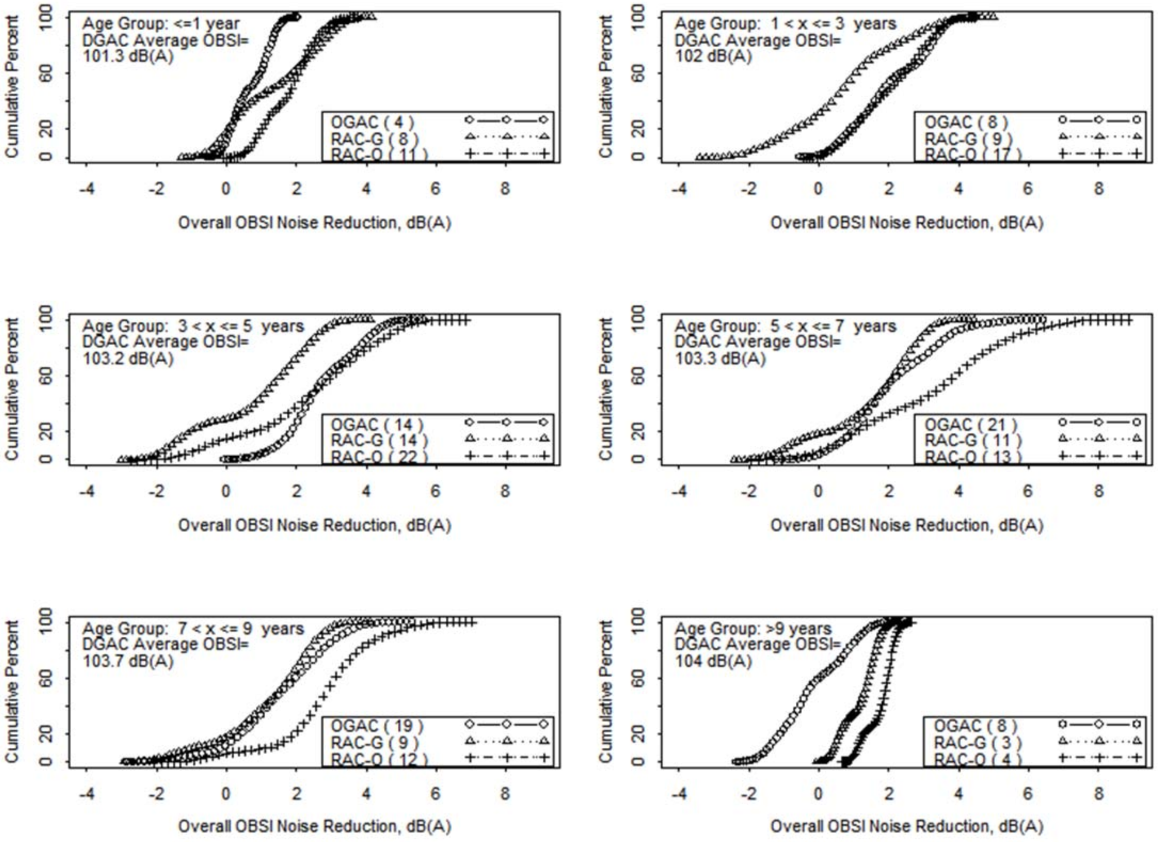


Figure A.9: The estimated cumulative distribution functions (CDF) of noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: [a.] A positive value indicates a reduction in noise. [b]. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

Multiple linear regression analysis was conducted to determine the effects of different variables on sound intensity levels and to construct prediction models for tire/pavement noise. A few pavement sections, as specified in the third- and fourth-year data analysis reports *(3, 6)*, were safely excluded from the data set used for this statistical analysis because they were either outliers or contained erroneous measurements in one year.

Separate regression models were proposed for determining the effects of mix type and mix properties on tire/pavement noise. In the first model, only the mix type (categorical variable) and environmental and traffic factors were included as the independent variables, while mix property variables other than NMAS were excluded. Because pavement condition data were not available, the MPD value was used as a surrogate for raveling as the only surface distress considered. The regression equation appears below as Equation A.5.2:

$$\begin{aligned}&\mathit{Overall\ Sound\ Intensity}(dBA)=101.9578+0.197\times Age(year)-3.7164\times ind(MixTypeOGAC)-1.6492\times ind(MixTypeRAC-G)\\&-3.0032\times ind(MixTypeRAC-O)-0.0180\times Thickness(mm)-0.0072\times NumberOfDays>30C\\&+0.0003\times MPD+0.2336\times Age\times ind(MixTypeOGAC)+0.0617\times Age\times ind(MixTypeRAC-G)-0.0375\times Age\times ind(MixTypeRAC-O)\end{aligned} \tag{A.5.2}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

Table A.16: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	101.9085	0.6123	166.4305	0
Age	**0.2102**	**0.0567**	**3.7092**	**0.0003**
PvmntTypeOGAC	**-3.4592**	**0.5627**	**-6.1475**	**0**
PvmntTypeRAC-G	**-1.4895**	**0.5184**	**-2.8732**	**0.0044**
PvmntTypeRAC-O	**-2.6141**	**0.5032**	**-5.1947**	**0**
Thickness	**-0.0145**	**0.0059**	**-2.4427**	**0.0153**
NoDaysTempGT30	**0.0056**	**0.002**	**2.7733**	**0.006**
AADTperLane	**0**	**0**	**2.1091**	**0.0359**
MPD	0	0.0003	-0.0493	0.9607
AgePvmntTypeOGAC	**0.202**	**0.0815**	**2.4791**	**0.0138**
AgePvmntTypeRAC-G	0.0357	0.0837	0.4263	0.6703
AgePvmntTypeRAC-O	-0.0847	0.0777	-1.0896	0.2769

Residual standard error: 1.422 on 254 degrees of freedom; Multiple R-Squared: 0.45

The R^2 shows that the model explains approximately of the variation in the dependent variable. The estimation results are very similar to the results based on the first five years of data *(3, 6)*, with only slight changes in the values of estimated parameters. Specifically, at the 95 percent confidence level, age, mix type, surface layer thickness, number of days with temperature greater than 30°C and AADT in the measured lane significantly affect the overall sound intensity. The three surface mix types, OGAC, RAC-G, and RAC-O, have lower initial overall sound intensity than DGAC. There is a significant two-factor interaction between age and OGAC mix type.

In the second model, the mix type variable was replaced with mix property variables, and the model was estimated for each mix type separately. The regression equations appear as Equation A.5.3 through Equation A.5.6:

For DGAC pavements

$$\begin{aligned}&\mathit{Overall\ Sound\ Intensity}(\mathit{dBA})\text{=102.2672-0.1747}\times\log(\mathit{Permeability})(\mathit{cm}/\sec)+0.0177\times\mathit{Age}(\mathit{year})-1.1368\times\mathit{FinenessModulus}\\&+0.0038\times\mathit{MPD}-0.0035\times\mathit{Thickness}(\mathit{mm})+0.0033\times\mathit{NumberOfDays}>30C+0.0001\times\mathit{AADTTinCoringLane}\end{aligned} \quad \textbf{(A.5.3)}$$

Table A.17: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	102.2672	3.5646	28.6894	0
log(Permeability)	-0.1747	0.1367	-1.2783	0.2174
Age	0.0177	0.053	0.3337	0.7424
FinenessModulus	-1.1674	0.774	-1.5084	0.1488
MPD	**0.0038**	**0.0013**	**2.9997**	**0.0077**
Thickness	-0.0035	0.0086	-0.4018	0.6926
NoDaysTempGT30	0.0033	0.0038	0.8757	0.3927
AADTTCoringLane	**0.0001**	**0**	**2.2497**	**0.0372**

Residual standard error: 0.741on 18 degrees of freedom; Multiple R-Squared: 0.69.

For OGAC pavements

$$\begin{aligned}&\mathit{Overall\ Sound\ Intensity}(\mathit{dBA})\text{=100.8937-0.1325}\times\log(\mathit{permeability})(\mathit{cm}/\sec)+0.374\times\mathit{Age}(\mathit{year})-0.8598\times\mathit{FinenessModulus}\\&+0.000\times\mathit{MPD}(\mathit{micron})-0.0025\times\mathit{Thickness}(\mathit{mm})+0.0054\times\mathit{NumberOfDays}>30C+0.0001\times\mathit{AADTTinCoringLane}\end{aligned} \quad \textbf{(A.5.4)}$$

Table A.18: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	100.8937	3.7366	27.0013	0
log(Permeability)	-0.1325	0.1247	-1.0631	0.2957
Age	**0.374**	**0.0716**	**5.2241**	**0**
FinenessModulus	-0.8598	0.6312	-1.3621	0.1827
MPD	0	0.0004	0.0784	0.938
Thickness	-0.0025	0.0117	-0.2128	0.8328
NoDaysTempGT30	0.0054	0.0041	1.3025	0.2021
AADTTCoringLane	**0.0001**	**0**	**4.7785**	**0**

Residual standard error: 0.9069 on 32 degrees of freedom; Multiple R-Squared: 0.76**.**

For RAC-G pavements

$$\begin{aligned}&\mathit{Overall\ Sound\ Intensity}(dBA)=96.7185\text{-}0.3602\times\log(permeability)(cm/\sec)+0.1221\times Age(year)-0.3255\times FinenessModulus\\&+0.0026\times MPD(micron)+0.0025\times Thickness(mm)+0.0095\times NumberOfDays>30C\end{aligned} \qquad \textbf{(A.5.5)}$$

Table A.19: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	96.7185	4.5632	21.1952	0
log(Permeability)	**-0.3602**	**0.1004**	**-3.5887**	**0.0015**
Age	0.1221	0.0715	1.7087	0.1004
FinenessModulus	-0.3255	0.9074	-0.3587	0.7229
MPD	**0.0026**	**0.0008**	**3.1993**	**0.0038**
Thickness	0.0025	0.0116	0.2131	0.8331
NoDaysTempGT30	**0.0095**	**0.0033**	**2.9267**	**0.0074**
AADTTCoringLane	0	0	0.9966	0.3289

Residual standard error: 0.8394 on 24 degrees of freedom; Multiple R-Squared: 0.76.

For RAC-O pavements

$$\begin{aligned}&\mathit{Overall\ Sound\ Intensity}(dBA)=114.3716+0.3798\times\log(permeability)(cm/\sec)+0.3337\times Age(year)-2.30384\times FinenessModulus\\&-0.0013\times MPD(micron)-0.0772\times Thickness(mm)-0.0001\times NumberOfDays>30C\end{aligned} \qquad \textbf{(A.5.6)}$$

Table A.20: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	113.0351	7.5874	14.8978	0
log(Permeability)	0.3598	0.2632	1.3671	0.1803
Age	**0.3331**	**0.1081**	**3.0807**	**0.004**
FinenessModulus	-1.7662	1.288	-1.3713	0.179
MPD	-0.0008	0.0011	-0.7609	0.4518
Thickness	**-0.09**	**0.0372**	**-2.4203**	**0.0208**
NoDaysTempGT30	-0.0022	0.0037	-0.5975	0.554
AADTperCoringLane	0	0	0.0359	0.9716

Residual standard error: 1.043 on 35 degrees of freedom; Multiple R-Squared: 0.39.

Except for the RAC-O mix model, the R^2 for the individual mix models are all above 0.60 which shows a moderate to good correlation and better than that of the combined model. Table A.21 shows a summary of the significant factors for all mixes.

Table A.21: Summary of Significant Factors for Overall OBSI for All Mixes

	DGAC	OGAC	RAC-G	RAC-O
Permeability			✓	
Age		✓		✓
FinenessModulus				
MPD	✓		✓	
Thickness				✓
NoDaysTempGT30			✓*	*
AADTTCoringLane	✓	✓		

The results show that overall sound intensity increases with pavement age for all the mix types but that it is only significant for the OGAC and RAC-O mixes. At the 95 percent confidence level, in-situ permeability is a significant factor for RAC-G. OGAC and RAC-O likely have consistently high permeability and DGAC consistently low permeability. Surface layer thickness is significant only for RAC-O, possibly due to the fact that for the other mix types the thicknesses were typically very similar. Thicker RAC-O mixes produced lower overall noise levels than thinner ones. Pavement surface macrotexture (MPD) is a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. For OGAC and RAC-O pavements, MPD does not have a significant influence on noise level.

For all the mix types, the aggregate gradation variable (fineness modulus) did not seem to significantly affect tire/pavement noise. Truck traffic volume was a significant factor that increased tire/pavement noise for OGAC and DGAC mixes, and it is interesting that the rubberized mixes were not sensitive to truck traffic. For RAC-G mixes, high temperature days (NoDaysTempGT30) is significant, and the estimated coefficient (0.0095) indicates that tire/pavement noise increases when the number of high temperature days increases, probably reflecting the densification under traffic observed in newly paved mixes of this type.

A.4.3 Evaluation of Sound Intensity Levels at One-Third Octave Frequency Bands

Sound intensity was analyzed at the following one-third octave frequency bands between 500 H and 5,000 Hz: 500 Hz, 630 Hz, 800 Hz, 1,000 Hz, 1,250 Hz, 1,600 Hz, 2,000 Hz, 2,500 Hz, 3,150 Hz, 4,000 Hz, and 5,000 Hz. Detailed statistical analysis in the report was performed for four typical frequency levels: 500 Hz, 1,000 Hz, 2,000 Hz, and 4,000 Hz.

Reference *(1)* presents a detailed description of the expected effects of the different tire/pavement noise–producing mechanisms on each one-third octave frequency.

A.4.3.1 Change of OBSI Spectra with Age

Figure 4.5 through Figure 4.7 show the sound intensity spectra averaged by mix type and initial age group in the six survey years. For more information, see Appendix B.5: Sound Intensity Spectra Measured Over Six Years for Each Pavement Section.

Figure 4.5 shows that over the first five years overall sound intensity changed little for newly paved overlays of both open-graded pavement mix types, OGAC and RAC-O. But in Year 6 the OGAC and RAC-O pavements exhibited an increase in low frequency content that indicates the development of raveling and higher MPD. More specifically, the spectra for these pavements show that the sound intensities increased in all the measured frequencies but more significantly for frequencies lower than 1,000 Hz. Increases seen in high-frequency noise indicate that the air-void content (or permeability) of the open-graded pavements decreased over the six years of data collection due to traffic action. On the other hand, the overall sound intensity for newly paved overlays of the DGAC and RAC-G pavement types increased in the higher frequencies in the first three years, and remained relatively unchanged in the fourth through sixth years. For these DGAC and RAC-G pavements, the low frequency noise decreased slightly with age over the six years of data collection. This indicates that the air-void content of the DGAC and RAC-G pavements decreased in the first three years after paving due to further compaction of mixes by action of traffic.

Figure 4.6 shows that for pavements with initial ages between one and four years at the start of the study, the sound intensity across all frequencies changed less with time on both rubberized pavements, RAC-G and RAC-O, but increased more on the DGAC and OGAC pavements. For frequencies below 1,000 Hz, sound intensity increased significantly for the RAC-G and DGAC pavements in the sixth year, while for the open-graded mix types it remained relatively unchanged over the six years. The RAC-O sections showed smaller changes than the other mixes across all six years of measurements.

Figure 4.7 shows that for the old pavements, i.e., with initial ages greater than four years, the overall sound intensity did not change significantly with age for the DGAC and RAC-G mixes, whereas for the open-graded mix types the figure shows that there were increases in noise for frequencies less than 1,000 Hz. This could be an indication of the onset of raveling on the open-graded mixes after about six to eight years of trafficking.

A.4.3.2 Descriptive Analysis of Sound Intensity Data for All One-Third Octave Bands

Figure A.10 through Figure A.20 show the six-year measurements of sound intensity at each one-third octave frequency band for all four mix types: DGAC, OGAC, RAC-G, and RAC-O. Sound intensity generally increases with pavement age at most frequency levels.

Figure A.10 and Figure A.11 show that at low-frequency levels (500 Hz and 630 Hz) sound intensities measured on the OGAC and RAC-O pavements are generally higher than the values measured on the DGAC and RAC-G pavements, especially for sixth year of data collection. This is because tire/pavement noise at low frequencies is governed by tire vibration, which is significantly affected by the macrotexture of pavement surfaces (identified by MPD) that generally tends to be larger on open-graded mixes. Figure A.12 shows that at a frequency level of 800 Hz, the sound intensities measured on the OGAC, RAC-G, and RAC-O pavements start to become lower than those measured on the DGAC pavements. This trend becomes more significant at higher frequency levels, where the air-pumping mechanism is expected to dominate, as shown in Figure A.13 through Figure A.20. The figures also show that for frequency levels equal to or larger than 1,000 Hz, the sound intensities measured on the OGAC and RAC-O pavements are generally lower than those measured on RAC-G pavements. This is primarily because the two open-graded pavements had higher air-void contents than the gap-graded pavements, and that greater air-void content reduced the tire/pavement noise caused by the air-pumping mechanism.

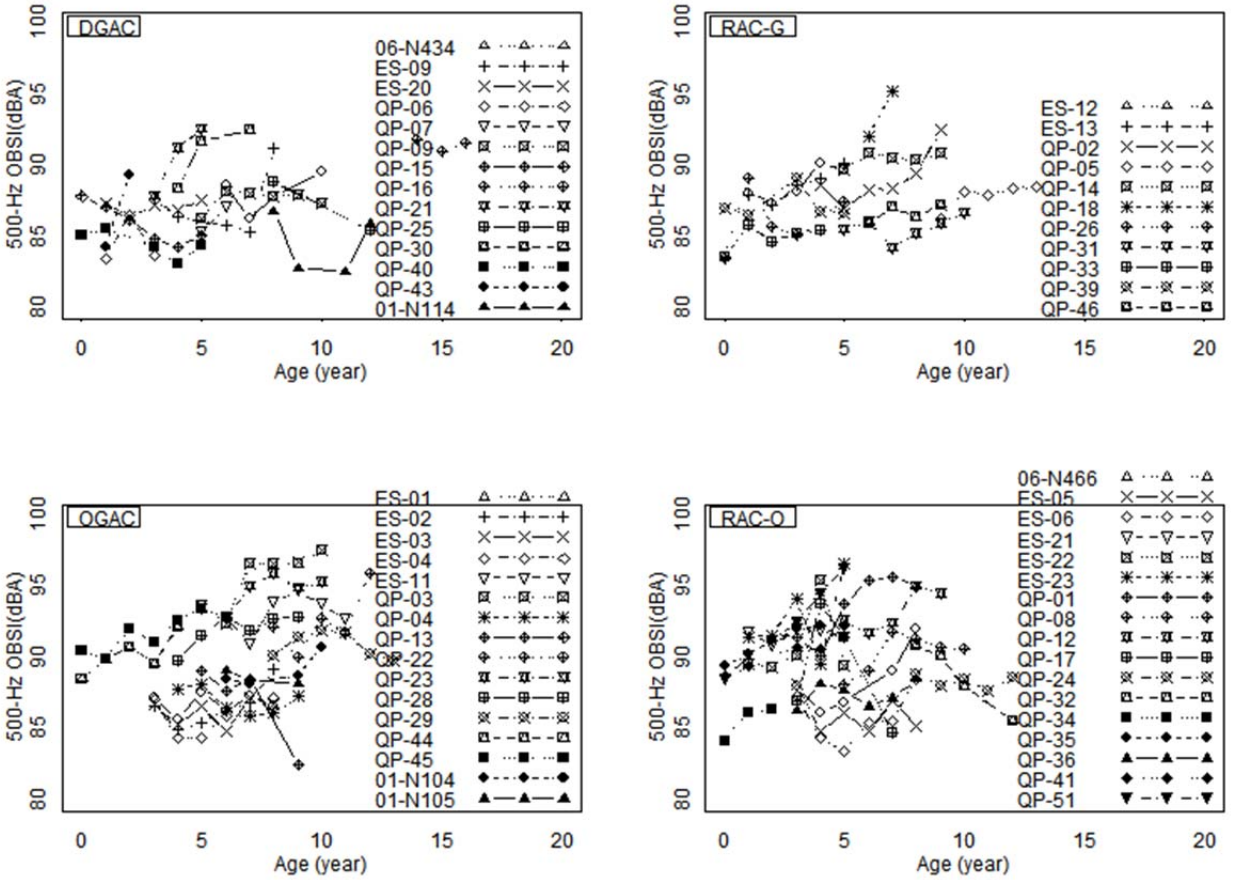


Figure A.10: Sound intensity at 500 Hz over six years for each pavement section.

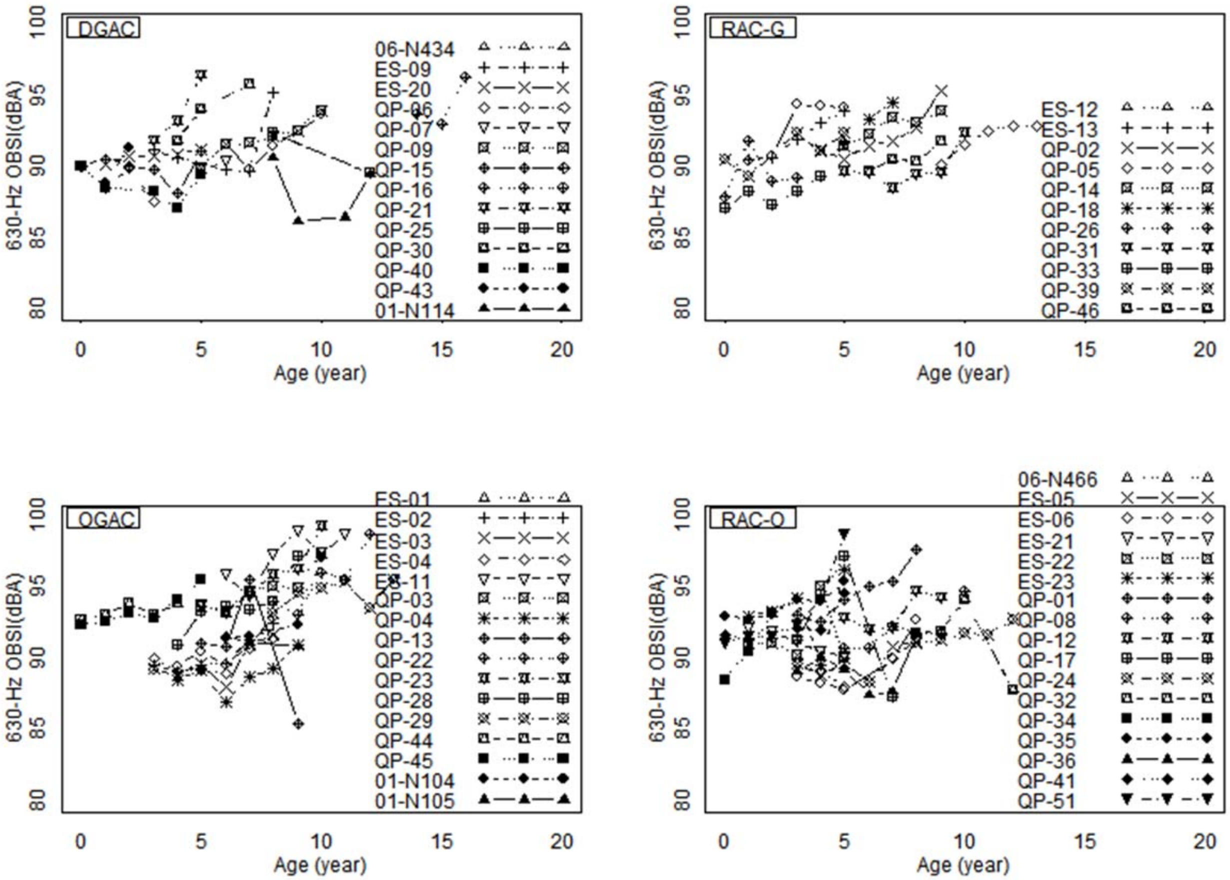


Figure A.11: Sound intensity at 630 Hz over six years for each pavement section.

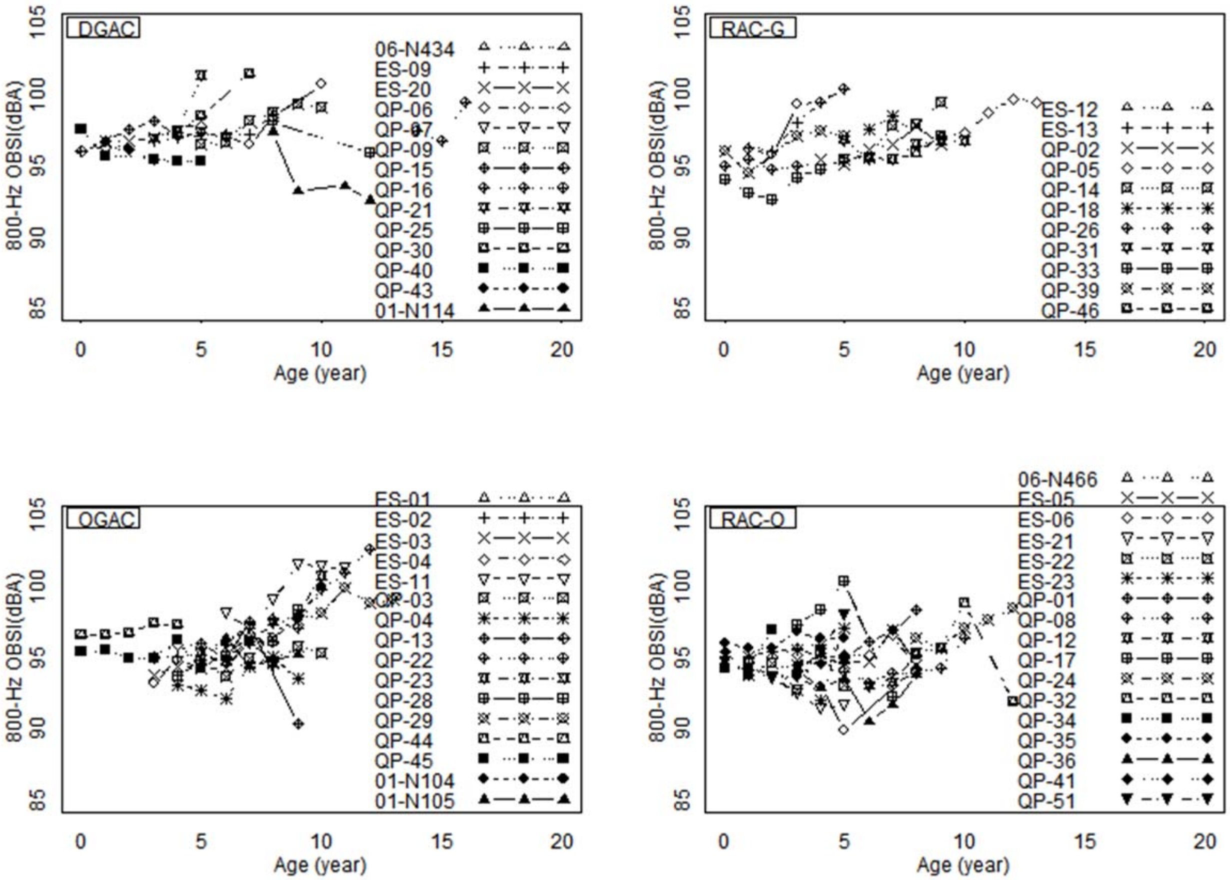


Figure A.12: Sound intensity at 800 Hz over six years for each pavement section.

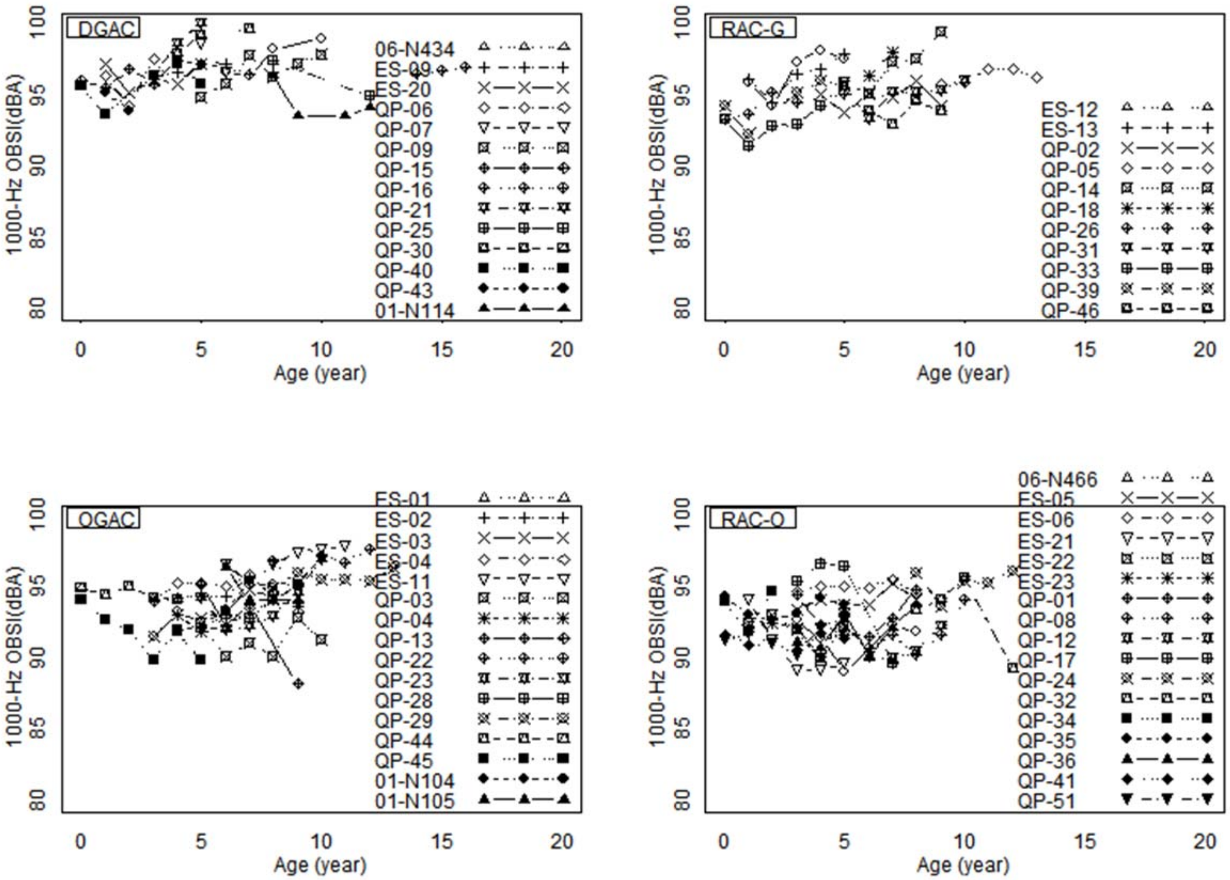


Figure A.13: Sound intensity at 1,000 Hz over six years for each pavement section.

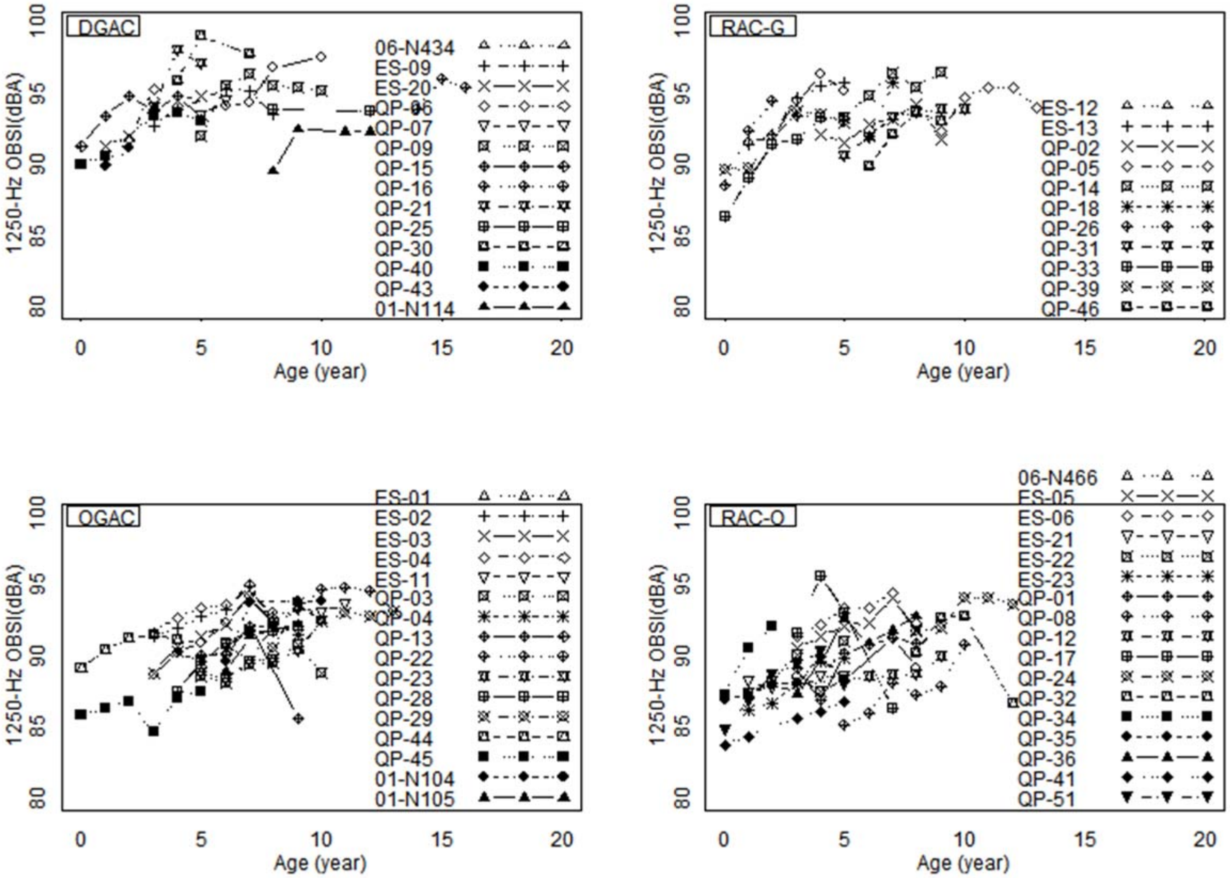


Figure A.14: Sound intensity at 1,250 Hz over six years for each pavement section.

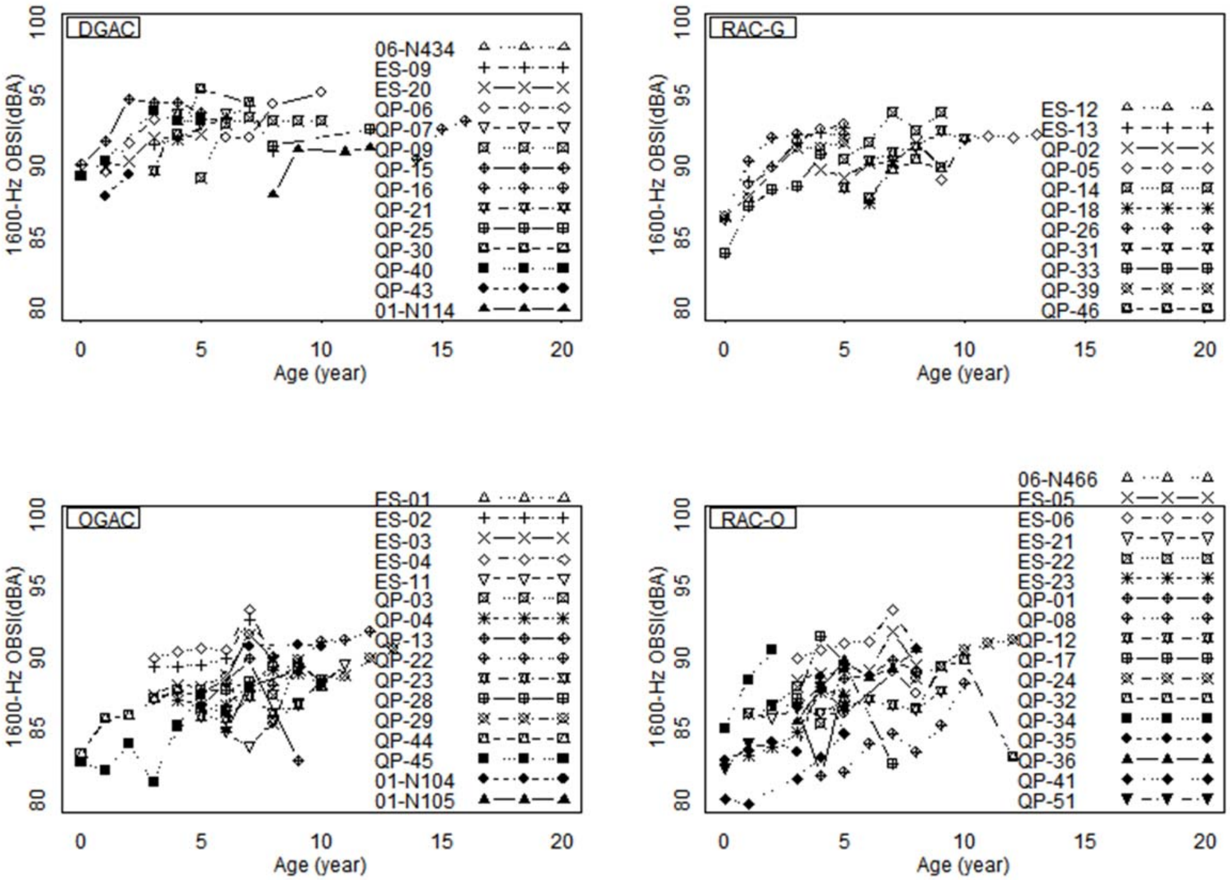


Figure A.15: Sound intensity at 1,600 Hz over six years for each pavement section.

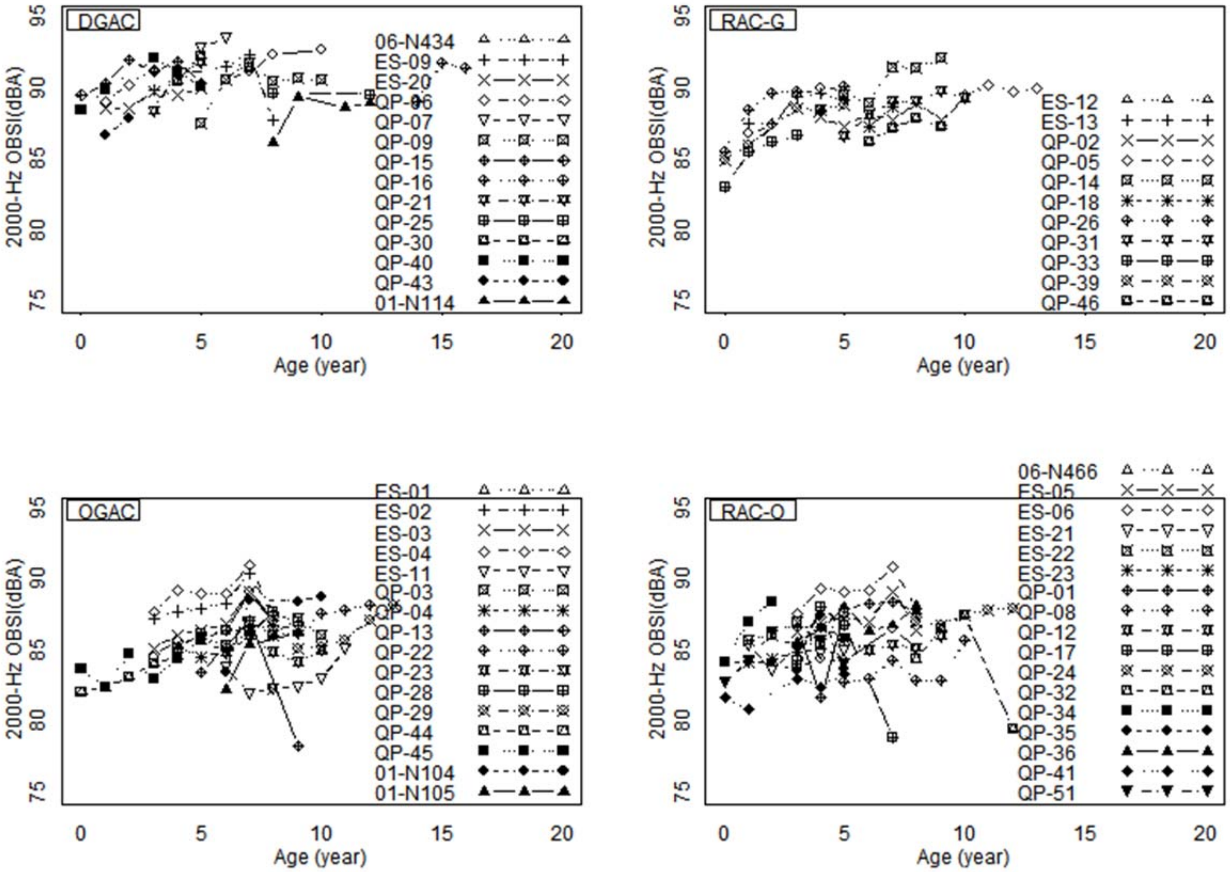


Figure A.16: Sound intensity at 2,000 Hz over six years for each pavement section.

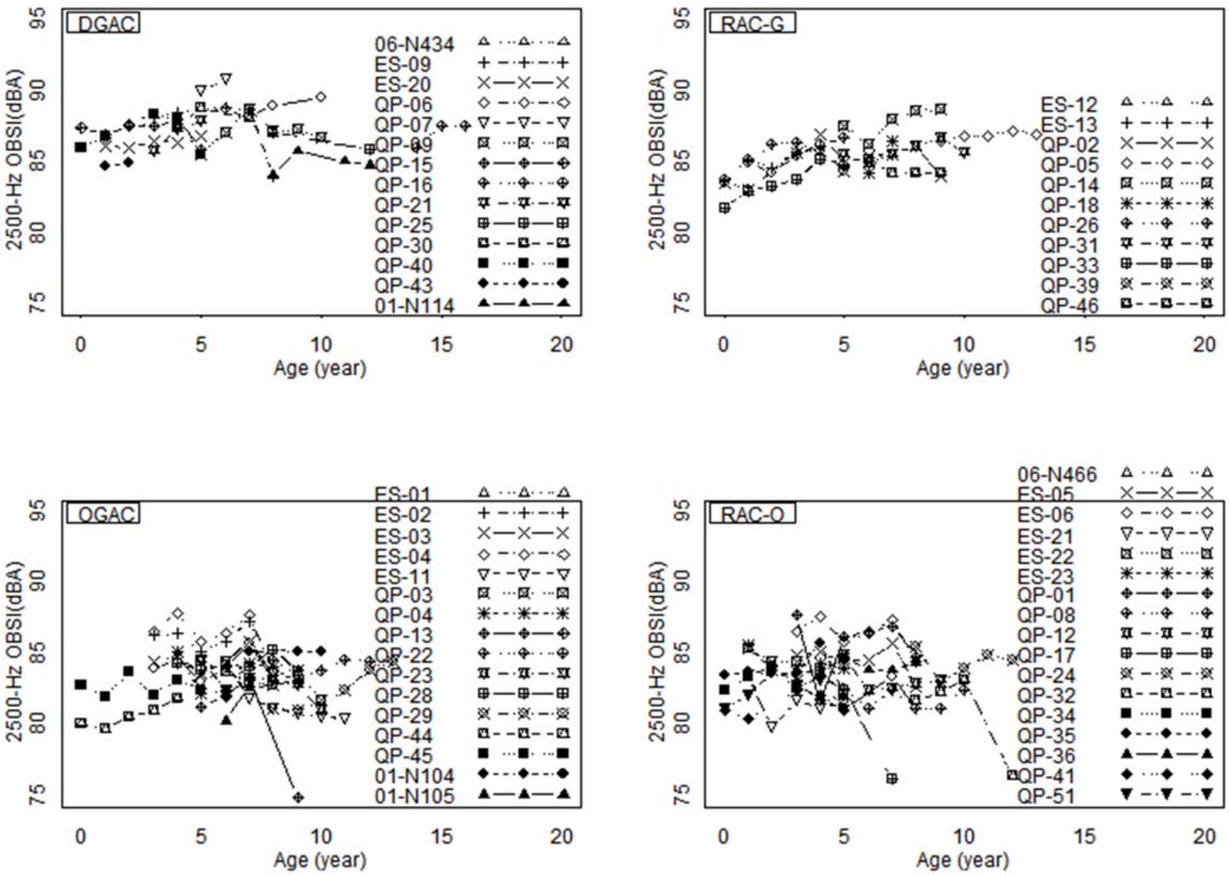


Figure A.17: Sound intensity at 2,500 Hz over six years for each pavement section.

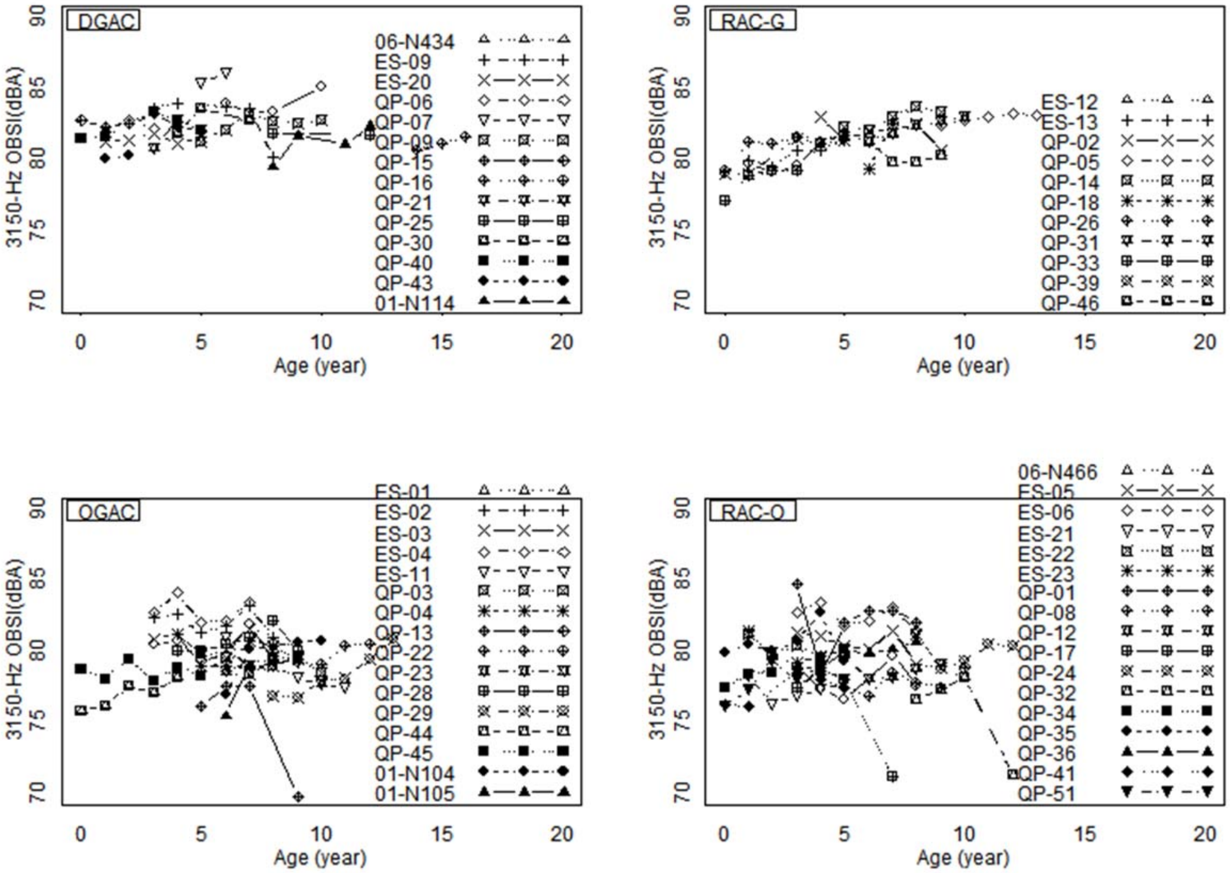


Figure A.18: Sound intensity at 3,150 Hz over six years for each pavement section.

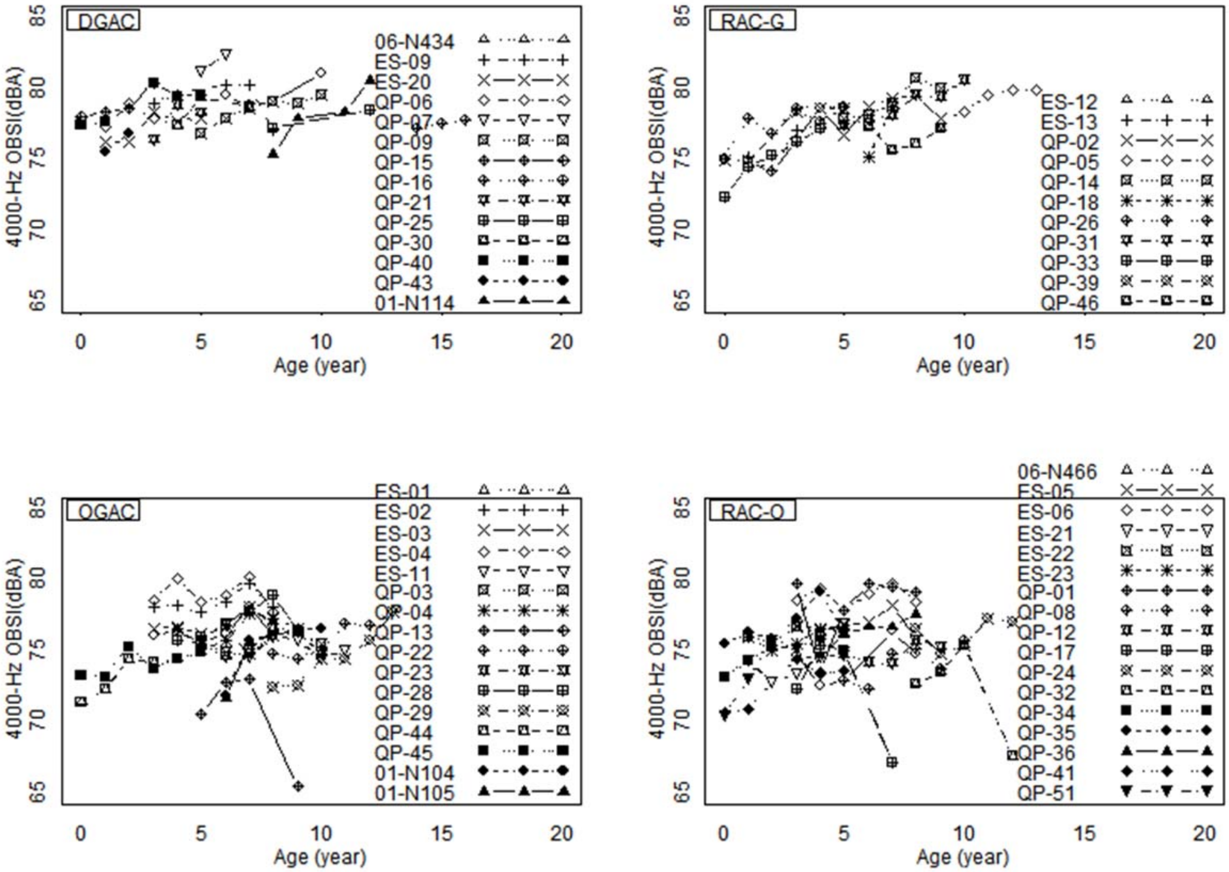


Figure A.19: Sound intensity at 4,000 Hz over six years for each pavement section.

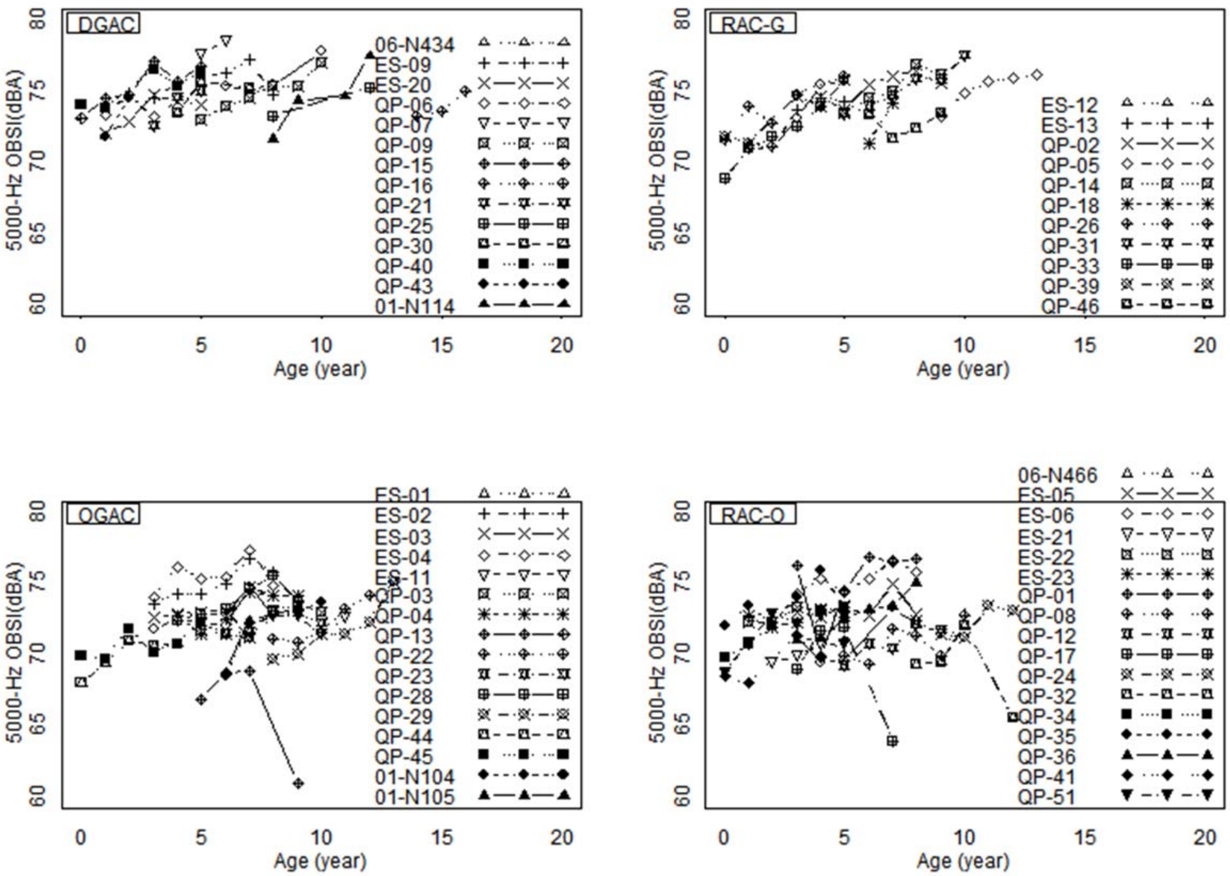


Figure A.20: Sound intensity at 5,000 Hz over six years for each pavement section.

A.4.3.3 Evaluation of Sound Intensity at the 500 Hz One-Third Octave Band

A.4.3.3.1 Descriptive Analysis

Figure A.10 shows the 500 Hz OBSI values observed on each pavement section of the four mix types over the six survey years. For newly paved sections, the 500 Hz sound intensity values measured on the open-graded pavements (OGAC and RAC-O) were generally higher than those measured on the dense- and gap-graded pavements (DGAC and RAC-G). For pavements with ages between four and seven years, no significant difference was apparent in 500 Hz sound intensity levels for the four mixes. For older pavements (those with ages greater than seven years), the OGAC pavements appear to have higher 500 Hz sound intensity than the other three pavement types. This indicates that OGAC pavements are more prone to raveling and to the other types of surface distresses that increase tire vibration and can lead to higher noise levels at this frequency. The variation in 500 Hz sound intensity among the different pavement sections, as shown in Figure A.21, appears to be higher for OGAC pavements than for the other pavement types. DGAC mixes had the lowest variability among the four mix types.

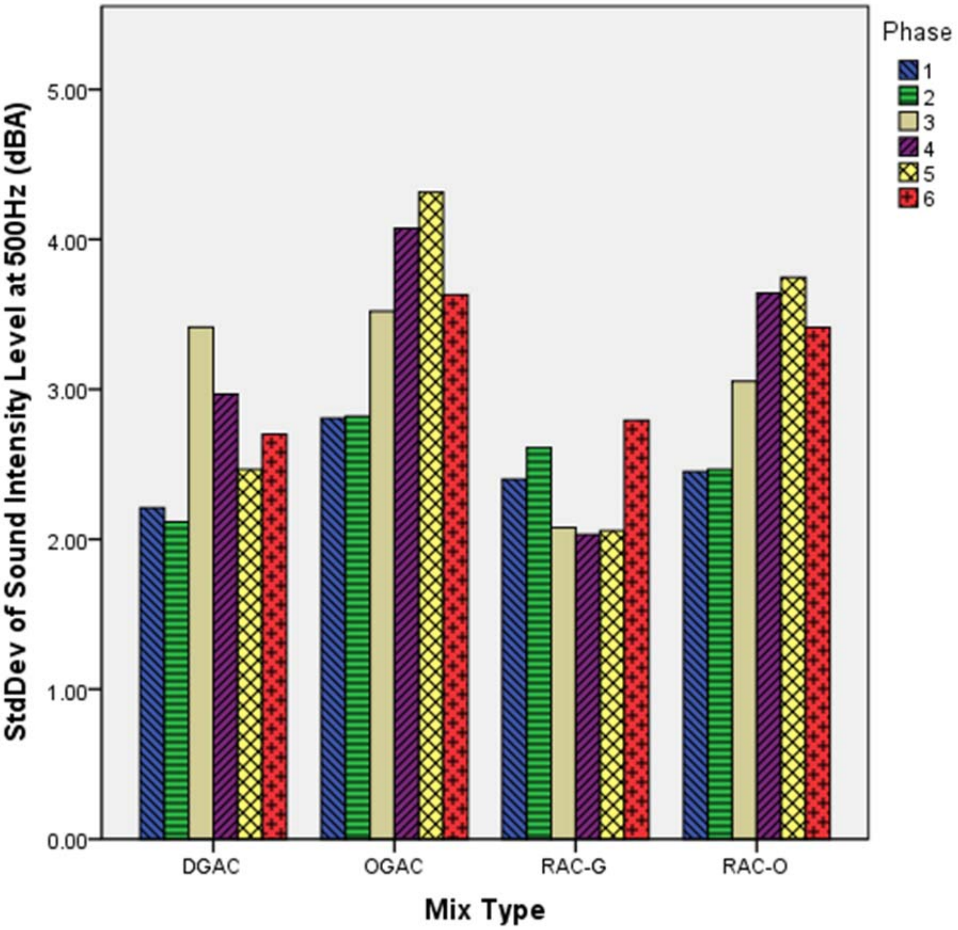


Figure A.21: Standard deviation of sound intensity at 500 Hz for different mix types for six years of data collection.

Figure A.22 shows box plots of the 500 Hz band OBSI over six years for all the different mix types and three age categories. As the figure shows, sound intensity generally increased with pavement age for each mix type. Overall, the rate of sound intensity increase was lower on the rubberized pavements (RAC-G and RAC-O) than on the nonrubberized pavements (DGAC and OGAC).

Figure A.23 can be used to compare the estimated cumulative distribution function of the 500 Hz noise reduction of the OGAC and RAC-O open-graded mixes and the RAC-G mixes against the average 500 Hz noise levels of the DGAC mixes for the six age groups. The average 500 Hz noise level on the DGAC pavements, as shown in the legend, was about 85.7 dBA for newly paved overlays, between 86.6 and 88.7 dBA for pavements with ages between three and nine years, and approximately 90.3 dBA for pavements older than nine years. A negative value in Figure A.23 indicates that the noise level increased relative to the average DGAC mix noise level. The figure shows that the noise change varied over a wide range for all the mixes, from -13 dBA to 6 dBA.

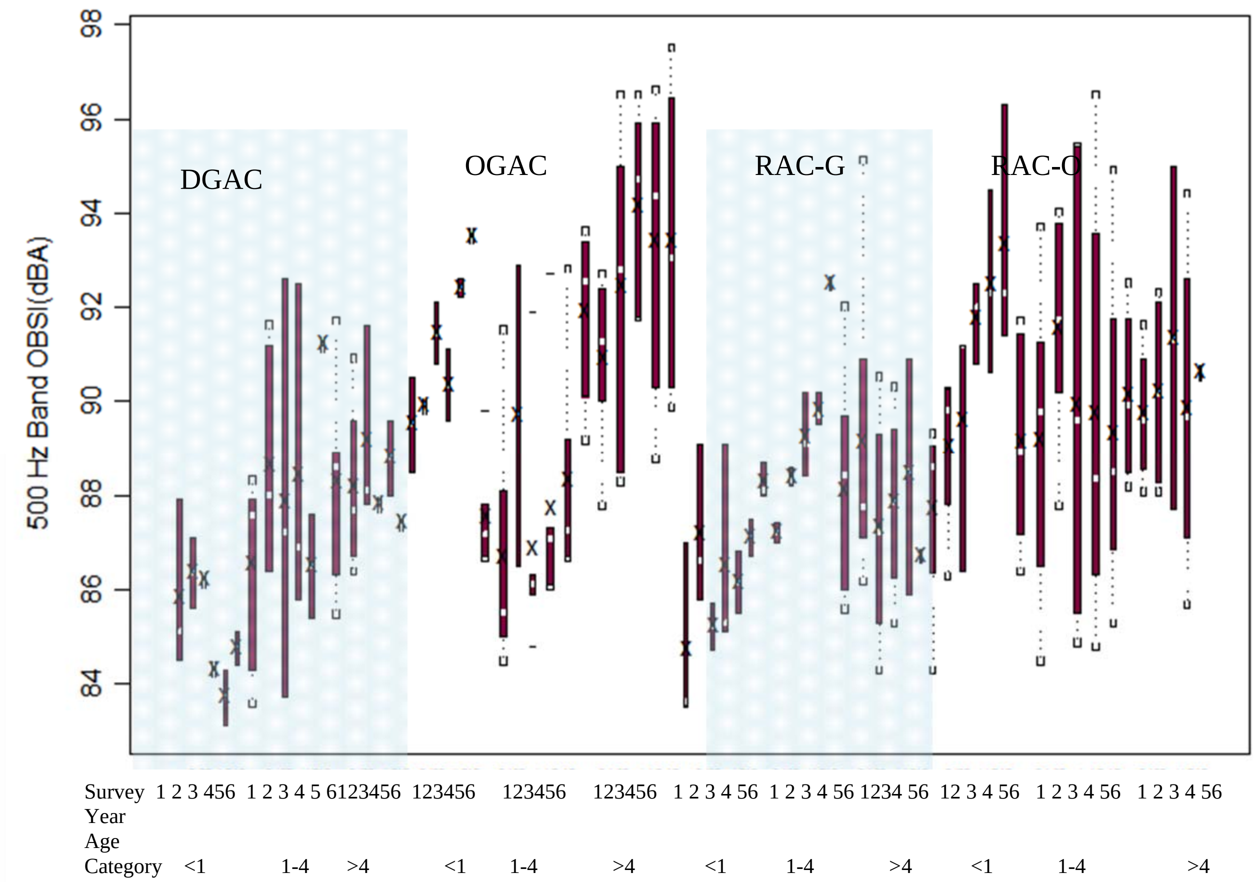


Figure A.22: Sound intensity at 500 Hz for different initial age categories (Age Category) and for six years of data collection.

For newly paved overlays (ages less than or equal to one year), the RAC-G pavements appear to have 500 Hz noise levels similar to DGAC pavements. About 40 percent of the pavements with a RAC-G mix on them were quieter than those with DGAC. The open-graded pavements were significantly noisier than the DGAC pavements. All the OGAC pavements and approximately 90 percent of the RAC-O pavements were noisier than the DGAC pavements.

Among the pavements with ages between one and three years, about 10 percent of the RAC-G, 40 percent of the OGAC, and 60 percent of the RAC-O were at least 3 dBA noisier than the DGAC pavements. In this age group, none of the mixes appeared to have a noise benefit over DGAC.

For pavements with ages between four and seven years, the RAC-G pavements appear to have noise characteristics similar to those of the DGAC mixes. The median of the noise reduction distribution curve was generally around 0 dBA for the RAC-G and OGAC mixes. The RAC-O showed higher noise between the ages of three to five years.

For the pavements with ages between seven and nine years, both the OGAC and RAC-O mixes were noisier than DGAC, while the RAC-G was quieter.

For the pavements with ages more than nine years, the RAC-G and RAC-O mixes showed similar noise characteristics and provided an approximate 3 dBA noise reduction over the DGAC mixes. The OGAC pavements were on average 3 dBA noisier than the DGAC pavements, and many were much noisier, most likely indicating tire vibration from raveling. A summary of the statistics for sound intensity at the 500 Hz frequency appears in Table A.22.

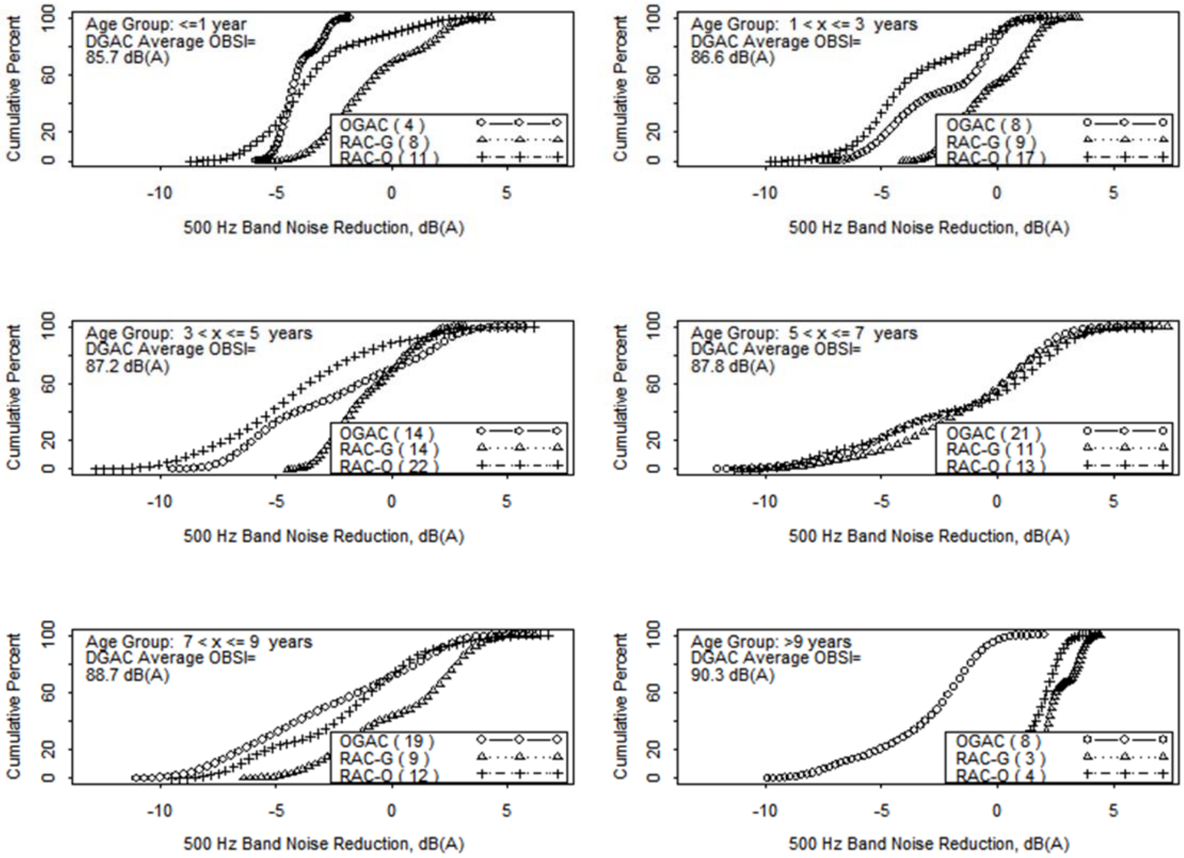


Figure A.23: Estimated cumulative distribution functions of the 500 Hz band noise reduction for all mixes for different groups by pavement age.
(Note: The number in parentheses in the legends represents the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

Table A.22: Summary Statistics for Sound Intensity at 500 Hz for All Mix Types

			Phase					
			1	2	3	4	5	6
Mix Type	DGAC	Valid N	15	13	8	6	8	5
		Mean	87.1	88.0	87.5	87.0	85.8	86.8
		Standard Deviation	2.2	2.1	3.4	3.0	2.5	2.7
		Minimum	83.5	85.6	82.8	84.3	82.6	84.4
		Maximum	91.8	91.7	92.6	92.5	89.6	91.2
		Range	8.3	6.1	9.8	8.2	7.0	6.8
	OGAC	Valid N	15	17	17	13	17	12
		Mean	90.0	89.2	90.1	90.2	89.7	90.8
		Standard Deviation	2.8	2.8	3.5	4.1	4.3	3.6
		Minimum	86.6	84.4	84.4	84.8	82.5	86.6
		Maximum	95.0	93.2	96.6	96.6	96.7	97.6
		Range	8.4	8.8	12.2	11.8	14.2	11.0
	RAC-G	Valid N	13	12	9	10	8	4
		Mean	87.4	88.2	87.2	87.9	88.4	88.4
		Standard Deviation	2.4	2.6	2.1	2.0	2.1	2.8
		Minimum	83.5	85.8	84.2	85.1	85.5	86.7
		Maximum	92.1	95.2	90.6	90.4	90.9	92.5
		Range	8.6	9.4	6.4	5.3	5.4	5.8
	RAC-O	Valid N	19	18	16	13	16	9
		Mean	89.3	89.1	89.7	90.7	90.2	91.1
		Standard Deviation	2.5	2.5	3.1	3.6	3.7	3.4
		Minimum	84.2	84.4	83.4	84.8	84.7	85.2
		Maximum	94.7	93.8	94.1	95.5	96.6	96.3
		Range	10.5	9.4	10.7	10.7	11.9	11.1

A.4.3.1.2 Statistical Analysis

A single-variable regression analysis was first conducted to determine the correlation between the dependent variable and each independent variable, and then a multiple regression model was performed to consider the effects of all variables on sound intensity. MPD was used as a surrogate for the surface distresses in the model (raveling). To determine the effects of mix type and mix properties on tire/pavement noise, separate regression models were proposed specifically for each mix type (*6)*.

In the first model, only the mix type (categorical variable) and environmental and traffic factors were included as independent variables, and the mix property variables were excluded. The regression equation appears below as Equation A.5.7::

$$\begin{aligned} &500Hz\ Sound\ Intensity(dBA)=6.0224+0.1682\times Age(year)+1.6936\times ind(MixTypeOGAC)-0.015\times ind(MixTypeRAC-G)\\ &+0.8844\times ind(MixTypeRAC-O)-0.0108\times Thickness(mm)-0.0134\times NumberOfDays>30C\\ &+0.0008\times AADTTinCoringLane+0.0017\times MPD \end{aligned} \tag{A.5.7}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

Table A.23: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	86.0224	0.9078	94.7596	0
Age	0.1682	0.0517	3.2524	0.0013
PvmntTypeOGAC	1.6936	0.5369	3.1545	0.0018
PvmntTypeRAC-G	-0.015	0.4962	-0.0303	0.9759
PvmntTypeRAC-O	0.8844	0.5401	1.6373	0.1028
Thickness	-0.0108	0.0101	-1.069	0.2861
NoDaysTempGT30	-0.0134	0.003	-4.5229	0
AADTTCoringLane	0.0008	0.0001	7.4336	0
MPD	0.0017	0.0005	3.569	0.0004

Residual standard error: 2.444 on 257 degrees of freedom; Multiple R-Squared: 0.42.

At the 95 percent confidence level, age, number of high temperature days, truck traffic in the coring lane, and MPD significantly affect the 500 Hz band sound intensity. Only the OGAC pavements exhibit a significant difference from DGAC mixes. The 500 Hz sound intensity increases with pavement age, truck traffic volume, and MPD, but decreases with number of high temperature days. The interaction terms between age and mix type are statistically insignificant, and they are not shown in the model above. This indicates that the growth rate of overall sound intensity is not statistically different for the four pavement types.

In the second set of models, the mix type variable was replaced with the mix property variables and the model was estimated for each mix type separately. The regression equations appear as Equation A.5.8 through Equation A.5.11. Using these multiple regression models one can determine the effect of individual factors on sound intensity.

<u>For DGAC pavements</u>

$$500Hz\ Sound\ Intensity(dBA)=81.0432+0.424\times AirVoid(\%)+0.1018\times Age(year)-0.565166\times FinenessModulus \\ +0.0068\times MPD+0.0184\times Thickness(mm)-0.0016\times NumberOfDays>30C \tag{A.5.8}$$

Table A.24: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	81.0432	5.4608	14.841	0
AirVoid	0.424	0.2444	1.7351	0.0989
Age	0.1018	0.1168	0.8718	0.3942
FinenessModulus	-0.5651	1.3462	-0.4198	0.6794
MPD	0.0068	0.0024	2.8031	0.0113
Thickness	0.0184	0.0203	0.9048	0.3769
NoDaysTempGT30	0.0016	0.0075	0.2176	0.83
AADTTCoringLane	0	0.0002	-0.1332	0.8955

Residual standard error: 1.522 on 19 degrees of freedom; Multiple R-Squared: 0.65.

<u>For OGAC pavements</u>

$$500Hz\ Sound\ Intensity(dBA)=100.2883+0.4306\times AirVoid(\%)+0.195\times Age(year)-2.9781\times FinenessModulus-0.001\times MPD(micron) \\ +0.0268\times Thickness(mm)-0.0376\times NumberOfDays>30C+0.0012\times AADTTinCoringLane \tag{A.5.9}$$

Table A.25: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	100.2883	5.5907	17.9383	0
AirVoid	0.4306	0.1404	3.0676	0.0044
Age	0.195	0.0962	2.0263	0.05
FinenessModulus	-2.9781	1.3447	-2.2147	0.034
MPD	-0.001	0.0007	-1.5823	0.1234
Thickness	0.0268	0.0251	1.0691	0.293
NoDaysTempGT30	-0.0376	0.0058	-6.5079	0
AADTTCoringLane	0.0012	0.0003	3.9823	0.0004

Residual standard error: 1.48 on 32 degrees of freedom; Multiple R-Squared: 0.82.

For RAC-G pavements

$$500Hz\ Sound\ Intensity(dBA) = 82.6918 - 0.2538 \times AirVoid(\%) + 0.0359 \times Age(year) + 0.4879 \times FinenessModulus + 0.0066 \times MPD(micron) \\ -0.0511 \times Thickness(mm) + 0.0102 \times NumberOfDays > 30C + 0.0007 \times AADTTinCoringLane \qquad \textbf{(A.5.10)}$$

Table A.26: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	82.6918	8.1439	10.1538	0
AirVoid	-0.2538	0.1826	-1.39	0.1784
Age	0.0359	0.1229	0.2918	0.7732
FinenessModulus	0.4879	1.7313	0.2818	0.7807
MPD	0.0066	0.0015	4.2759	0.0003
Thickness	-0.0511	0.0258	-1.98	0.0603
NoDaysTempGT30	0.0102	0.0059	1.7161	0.1002
AADTTCoringLane	0.0007	0.0004	1.8748	0.0742

Residual standard error: 1.559 on 22 degrees of freedom; Multiple R-Squared: 0.67.

For RAC-O pavements

$$500Hz\ Sound\ Intensity(dBA) = 81.5994 + 0.1464 \times AirVoid(\%) + 0.105 \times Age(year) + 0.2744 \times FinenessModulus + 0.0047 \times MPD(micron) \\ -0.0015 \times Thickness(mm) - 0.0142 \times NumberOfDays > 30C + 0.0005 \times AADTTinCoringLane \qquad \textbf{(A.5.11)}$$

Table A.27: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	80.6523	12.8387	6.282	0
AirVoid	0.1464	0.2008	0.7291	0.4705
Age	0.105	0.151	0.6952	0.4913
FinenessModulus	0.2744	2.8846	0.0951	0.9247
MPD	0.0047	0.002	2.3407	0.0247
Thickness	-0.0015	0.0462	-0.0319	0.9747
NoDaysTempGT30	-0.0142	0.0083	-1.7159	0.0945
AADTTCoringLane	0.0005	0.0002	2.3451	0.0245

Residual standard error: 2.226 on 37 degrees of freedom; Multiple R-Squared: 0.53.

All four models show large variance in residual errors, which indicates that the data used in the analysis have high inherent variability. Age is not a significant factor for any of the pavement types except OGAC at the 95 percent confidence level, indicating that older OGAC pavements have a significantly higher noise level at 500 Hz, presumably due to the loss of the aggregate form surface course. Truck traffic volume is a significant factor that contributes to the increase of the 500 Hz band noise for open-graded mixes and gap-graded mixes but not for dense-graded mixes, indicating the potential damage that trucks impose on open-graded and gap-graded pavements.

As can be seen in Table A.28, among the four mix types, air-void content is statistically significant at the 95 percent confidence level only for OGAC and DGAC pavements. The estimated coefficient indicates that higher air-void content is correlated with the 500 Hz band noise, although this is probably not a causal relationship.

For OGAC pavements, the aggregate gradation variable (fineness modulus) seems to significantly affect low-frequency noise. The number of high temperature days is a statistically significant variable for open-graded mixes. More high temperature days tend to result in lower low-frequency noise on the OGAC and RAC-O pavements, most likely because stones protruding from the surface of the mix are pushed down.

MPD is a statistically significant variable for the DGAC, RAC-G, and RAC-O pavements. A higher MPD value (i.e., higher macrotexture) increases tire vibration and tends to increase low-frequency noise. For RAC-G mixes thickness is significant at the 10 percent confidence level, and thicker pavements produce lower noise than thin pavements.

Table A.28: Summary of Significant Factors for All Mixes at 500 Hz

	DGAC	OGAC	RAC-G	RAC-O
Air Void	✓*	✓		
Age		✓		
FinenessModulus		✓		
MPD	✓		✓	✓
Thickness			✓*	
NoDaysTempGT30		✓		✓*
AADTTCoringLane		✓	✓*	✓

A.4.3.4 Evaluation of Sound Intensity at the 1,000 Hz One-Third Octave Band

A.4.3.4.1 Descriptive Analysis

Figure A.13 and Table A.29 show the 1,000 Hz OBSI values observed in the six survey years on each pavement section for the four mix types. Noise at 1,000 Hz is in the frequency range most perceived by humans, and has a high weighting in the dBA scale. Generally the 1,000 Hz sound intensity increased with pavement age, except for the RAC-O mix type where there did not appear to be much of an increase regardless of age. For newly paved overlays, the 1,000 Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) were lower than the values measured on dense-graded pavements (DGAC). Sound intensity at 1,000 Hz is a function of both tire vibration and the air-pumping effect, and most likely is affected by tire tread pattern and not by pavement characteristics.

Figure A.24 shows the box plots of the 1,000 Hz band OBSI for six years of measurement for the different mix types and for the three initial age categories. Other than a few exceptions in the RAC-O mixes, sound intensity increased with age and this trend is also obvious among different pavement sections of the same mix type. Overall, the rate of increase of sound intensity was lowest on RAC-O pavements, which indicates that these pavements retain their noise-reducing properties over a longer period.

Table A.29: Summary Statistics for Sound Intensity at 1,000 Hz for All Mix Types

			Phase					
			1	2	3	4	5	6
Mix Type	DGAC	Valid N	15	13	8	6	8	5
		Mean	96.5	96.1	97.2	96.9	96.7	96.5
		Standard Deviation	1.1	1.7	1.9	1.5	1.7	1.5
		Minimum	94.7	93.7	93.6	95.9	93.6	94.2
		Maximum	98.7	99.3	100.1	99.7	99.0	97.9
		Range	4.0	5.6	6.5	3.8	5.4	3.7
	OGAC	Valid N	15	17	17	13	17	12
		Mean	93.9	93.5	93.7	93.8	94.0	94.8
		Standard Deviation	1.7	1.8	2.0	2.2	3.1	2.4
		Minimum	91.6	90.2	89.9	89.9	85.5	89.9
		Maximum	96.9	96.5	97.2	97.5	97.7	97.9
		Range	5.3	6.3	7.3	7.6	12.2	8.0
	RAC-G	Valid N	13	12	9	10	8	4
		Mean	95.3	94.1	95.7	95.6	96.7	95.3
		Standard Deviation	1.1	1.7	1.5	1.7	1.6	.8
		Minimum	93.4	91.5	92.9	93.0	94.3	94.3
		Maximum	96.7	98.1	97.4	98.2	99.5	96.1
		Range	3.3	6.6	4.5	5.2	5.2	1.8
	RAC-O	Valid N	19	18	16	13	16	9
		Mean	93.4	92.5	92.8	91.5	92.6	93.5
		Standard Deviation	1.4	1.7	2.3	2.1	2.0	1.2
		Minimum	91.2	90.1	89.1	89.2	89.3	91.5
		Maximum	96.1	96.7	96.5	95.3	96.2	94.9
		Range	4.9	6.6	7.4	6.1	6.9	3.4

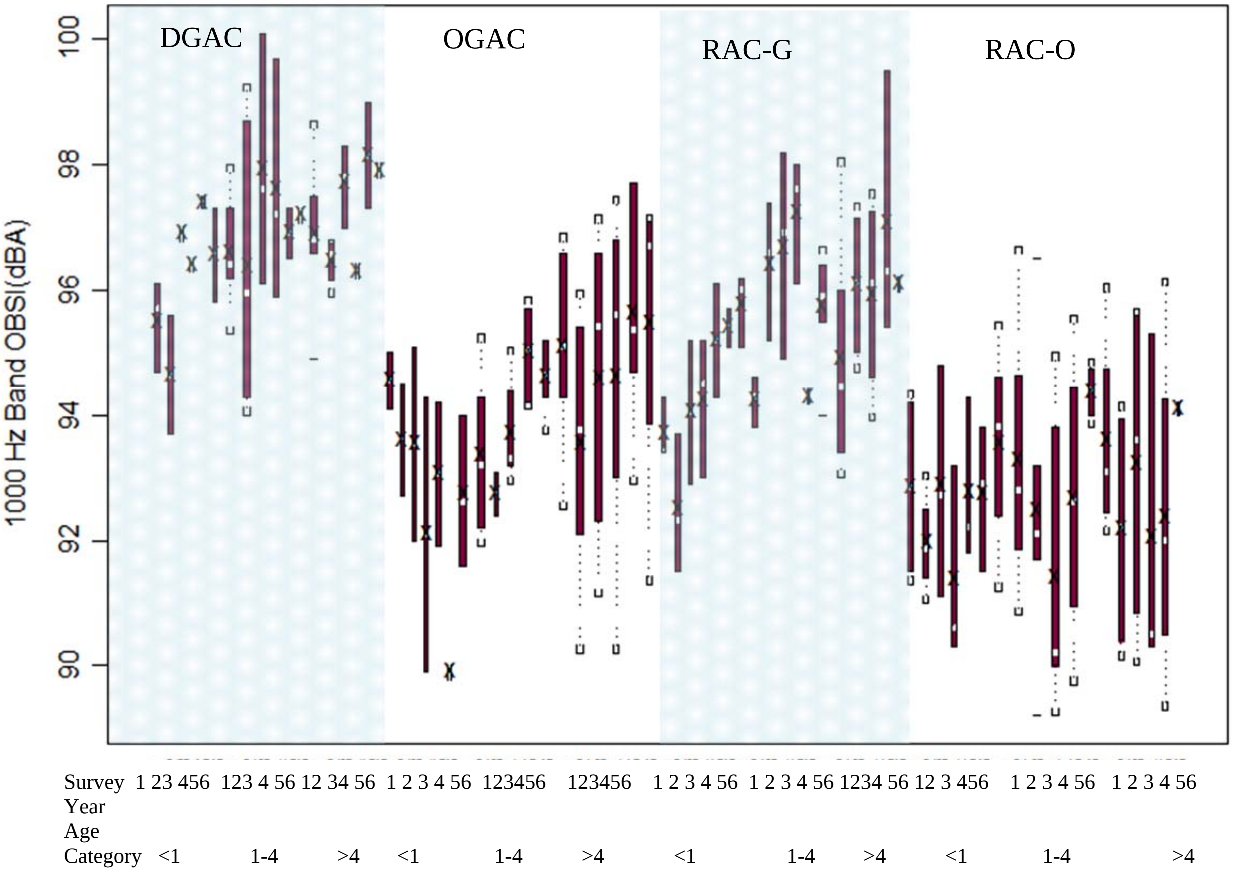


Figure A.24: Sound intensity at 1,000 Hz for different initial age categories (Age Category) and for six years of data collection.

Figure A.25 shows the estimated cumulative distribution function of 1,000 Hz noise reduction for both the OGAC and RAC-O open-graded mixes and the RAC-G mixes compared to the average 1,000 Hz noise levels of the DGAC mixes in the six age groups. The average 1,000 Hz noise level on DGAC pavements, as shown in the legend, was approximately 95.6 dBA for newly paved overlays, between approximately 95.9 and 97.3 dBA for pavements with ages between three and nine years, and approximately 97.5 dBA for pavements older than nine years. A negative value in Figure A.25 indicates an increase in noise levels compared to the average DGAC mix noise level. The figure shows that except for pavements older than nine years, the OGAC and RAC-O pavements were all generally quieter than the DGAC pavements in terms of 1,000 Hz band noise. Between 10 to 30 percent of the RAC-G pavements with ages between three and nine years produced louder noise than the dense-graded mixes.

For newly paved overlays (with ages less than or equal to one year), the OGAC and RAC-G pavements seem to have similar noise-reducing properties, with both showing noise reductions of 3 dBA or more compared to DGAC for about 20 percent of the sections. The RAC-O pavements seemed to reduce noise more effectively than OGAC and RAC-G. If a noise reduction of at least 3 dBA is required for a surface to be considered noise-reducing, about 10 percent of OGAC and 20 percent of RAC-G pavements are noise-reducing, but about 50 percent of the RAC-O pavements are noise-reducing compared with DGAC of the same age. This suggests construction of RAC-O pavements in noisy areas is a good method for reducing environmental noise.

For pavements with ages between one and five years, OGAC and RAC-O pavements had similar noise-reducing properties (about 70 percent of these pavements were at least 3 dBA quieter than the average DGAC pavement), while RAC-G pavements had lost most of their noise-reducing effect.

For pavements with ages between five and nine years, both OGAC and RAC-O pavements still performed better than RAC-G pavements, but RAC-O pavements clearly performed better than OGAC pavements. Seven years after construction about 70 percent of the RAC-O and 25 percent of the OGAC pavements could satisfactorily perform as a noise mitigation tool, while only 10 percent of RAC-G pavements provided the defining 3 dBA noise reduction compared to the DGAC pavements. Interestingly, some RAC-O pavements could provide a noise-reducing effect of up to 6 dBA compared to DGAC pavements of similar age.

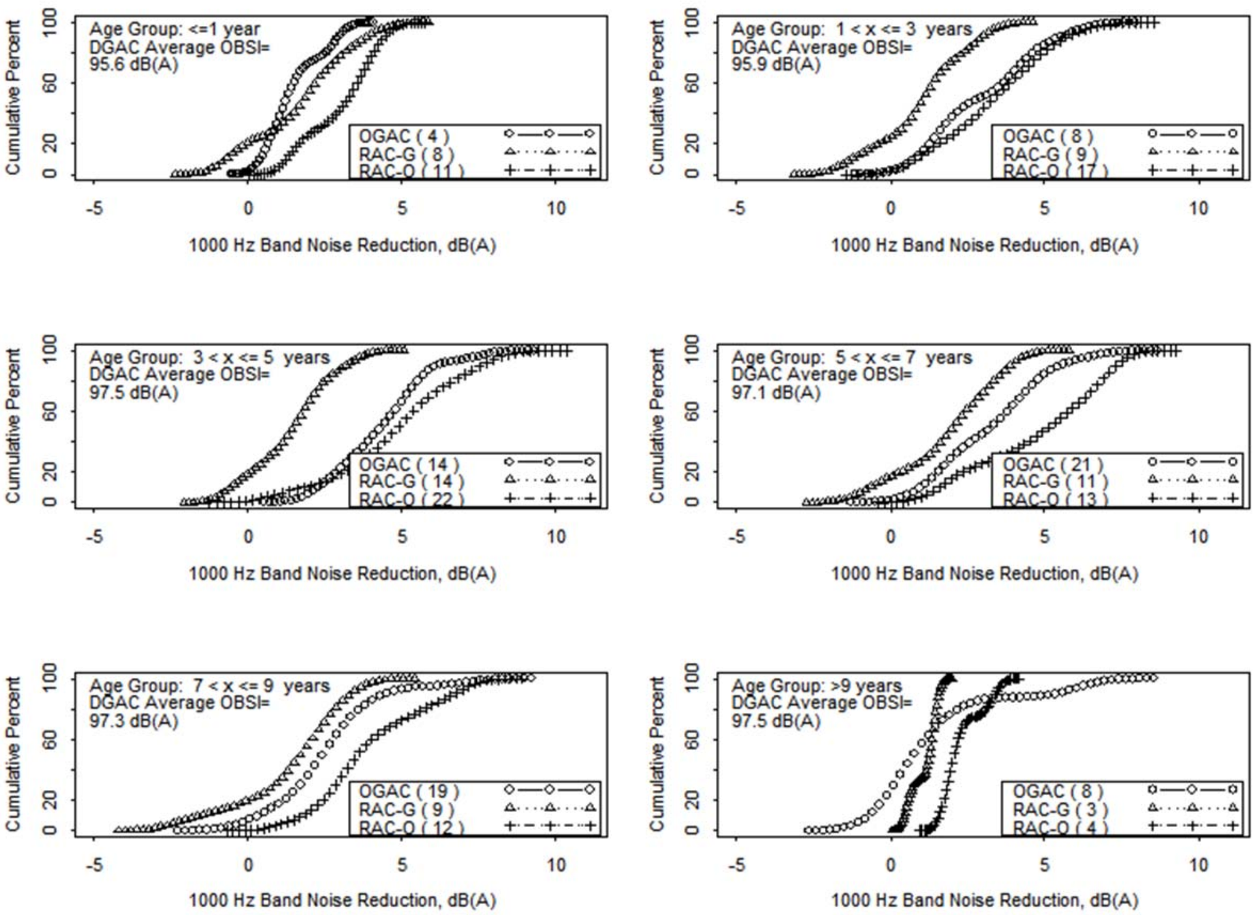


Figure A.25: Estimated cumulative distribution function of 1,000 Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of the DGAC mixes in each age group.)

A small sample of pavements older than nine years suggests that only a small portion of OGAC pavements still performed well and provided satisfactory noise characteristics compared to DGAC pavements. Hence, the rank of the three mixes from best to worst is: RAC-O, RAC-G, OGAC.

A.4.3.4.2 Statistical Analysis

Multiple regression analysis was conducted to account for the effects of various variables simultaneously. Two separate regression models were proposed. MPD was used as a surrogate for surface distresses, primarily raveling. In the first model, only the mix type (categorical variable) and environmental and traffic factors were included as independent variables, while the mix property variables were excluded. The regression equation appears as Equation A.5.12:

$$\begin{aligned}&1000Hz\ Sound\ \ Intensity(dBA){=}96.9784{+}0.2085\times Age(year)-3.3753\times ind(MixTypeOGAC)-1.5512\times ind(MixTypeRAC-G)\\&-4.7398\times ind(MixTypeRAC-O)-0.0289\times Thickness(mm)+0.0102\times NumberOfDays>30C\\&-0.0005\times MPD\end{aligned} \tag{A.5.12}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

Table A.30: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	96.7436	0.6034	160.3233	0
Age	0.2032	0.0344	5.9113	0
PvmntTypeOGAC	-3.3167	0.3569	-9.2936	0
PvmntTypeRAC-G	-1.4958	0.3298	-4.5352	0
PvmntTypeRAC-O	-4.7114	0.359	-13.122	0
Thickness	-0.023	0.0067	-3.4437	0.0007
NoDaysTempGT30	0.0086	0.002	4.3377	0
AADTTCoringLane	0.0001	0.0001	1.3242	0.1866
MPD	-0.0005	0.0003	-1.5842	0.1144

Residual standard error: 1.625 on 257 degrees of freedom; Multiple R-Squared: 0.53.

At the 95 percent confidence level, 1,000 Hz sound intensity level is significantly influenced by several factors such as age, mix type, surface layer thickness, and number of high temperature days. The 1,000 Hz sound intensity increases with pavement age and temperature, but decreases with surface layer thickness. Among the three pavement types, OGAC, RAC-G, and RAC-O, all have lower initial 1,000 Hz sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for all OGAC, RAC-G, and RAC-O mixes over the course of the study are about 3.3 dBA, 1.5 dBA, and 4.7 dBA, respectively. The interaction terms between age and mix type were studied and were found to not be statistically significant, so they were not included in the model above. This indicates that the overall growth rate of 1,000 Hz sound intensity is not statistically different for the four pavement types.

In the second model, the mix type variable was replaced with the mix property variables and the model was estimated for each mix type separately. The regression equations appear as Equation A.5.13 through Equation A.5.16:

For DGAC pavements

$$1000Hz\ Sound\ \ Intensity(dBA){=}95.24{+}0.3441\times AirVoid(\%)-0.0698\times Age(year)-1.0771\times FinenessModulus \\ +0.004\times MPD+0.0054\times Thickness(mm)+0.0044\times NumberOfDays>30C+0.0004\times AADTTinCoringLane \quad \textbf{(A.5.13)}$$

Table A.31: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	95.24	4.0077	23.7644	0
AirVoid	0.3441	0.1794	1.9187	0.0702
Age	-0.0698	0.0857	-0.8149	0.4252
FinenessModulus	-1.0771	0.988	-1.0902	0.2893
MPD	**0.004**	**0.0018**	**2.2327**	**0.0378**
Thickness	0.0054	0.0149	0.3637	0.7201
NoDaysTempGT30	0.0044	0.0055	0.8044	0.4311
AADTTCoringLane	**0.0004**	**0.0002**	**2.3788**	**0.028**

Residual standard error: 1.112 on 19 degrees of freedom; Multiple R-Squared: 0.54.

For OGAC pavements

$$1000Hz\ Sound\ \ Intensity(dBA){=}98.7512{-}0.1307\times AirVoid(\%)+0.216\times Age(year)-0.8694\times FinenessModulus+0.0005\times MPD(micron) \\ -0.0374\times Thickness(mm)+0.008\times NumberOfDays>30C+0.0008\times AADTTinCoringLane \quad \textbf{(A.5.14)}$$

Table A.32: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	98.7512	5.2304	18.8804	0
AirVoid	-0.1307	0.1313	-0.9953	0.3271
Age	**0.216**	**0.09**	**2.3995**	**0.0224**
FinenessModulus	-0.8694	1.258	-0.6911	0.4945
MPD	0.0005	0.0006	0.8935	0.3783
Thickness	-0.0374	0.0235	-1.592	0.1212
NoDaysTempGT30	0.0063	0.0054	1.1556	0.2564
AADTTCoringLane	**0.0008**	**0.0003**	**2.7639**	**0.0094**

Residual standard error: 1.385 on 32 degrees of freedom; Multiple R-Squared: 0.54.

For RAC-G pavements

$$1000Hz\ Sound\ Intensity(dBA)=85.6077\text{-}0.1944\times AirVoid(\%)+0.2287\times Age(year)+1.8043\times FinenessModulus+0.0015\times MPD(micron) \\ -0.0239\times Thickness(mm)+0.0124\times NumberOfDays>30C+0.0001\times AADTTinCoringLane \quad \textbf{(A.5.15)}$$

Table A.33: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	85.6077	6.5926	12.9853	0
AirVoid	-0.1944	0.1478	-1.3149	0.2021
Age	**0.2287**	**0.0995**	**2.2987**	**0.0314**
FinenessModulus	1.8043	1.4015	1.2874	0.2113
MPD	0.0015	0.0012	1.1797	0.2507
Thickness	-0.0239	0.0209	-1.1437	0.265
NoDaysTempGT30	**0.0124**	**0.0048**	**2.5874**	**0.0168**
AADTTCoringLane	0.0001	0.0003	0.3142	0.7563

Residual standard error: 1.262 on 22 degrees of freedom; Multiple R-Squared: 0.52.

For RAC-O pavements

$$1000Hz\ Sound\ Intensity(dBA)=104.119+0.067\times AirVoid(\%)+0.2123\times Age(year)-1.285\times FinenessModulus-0.0028\times MPD(micron) \\ -0.1041\times Thickness(mm)-0.0001\times AADTTinCoringLane \quad \textbf{(A.5.16)}$$

Table A.34: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	104.119	8.0434	12.9447	0
AirVoid	0.067	0.1258	0.5326	0.5975
Age	**0.2123**	**0.0946**	**2.2438**	**0.0309**
FinenessModulus	-1.285	1.8072	-0.7111	0.4815
MPD	**-0.0028**	**0.0012**	**-2.2742**	**0.0288**
Thickness	-0.1041	0.0289	-3.6002	0.0009
NoDaysTempGT30	0	0.0052	-0.0037	0.9971
AADTTCoringLane	-0.0001	0.0001	-1.0758	0.289

Residual standard error: 1.395 on 37 degrees of freedom; Multiple R-Squared: 0.50.

Table A.35 summarizes the significant factors for each mix type.

Table A.35: Summary of Significant Factors for All Mixes at 1,000 Hz

	DGAC	OGAC	RAC-G	RAC-O
Air Void				
Age		✓	✓	✓
FinenessModulus				
MPD	✓			✓
Thickness				✓
NoDaysTempGT30			✓	
AADTTCoringLane	✓	✓		

The results of the analysis show that all the regression equations had low R^2 values (around 0.50), indicating that there are explanatory variables other than the traffic, climate, and pavement variables that need to be considered to explain the variability of the noise level at this frequency. The tire tread pattern for the SRTT is likely the main factor contributing the noise level for this frequency. Because no quantified variable to define the tire tread pattern was available, further analysis of the effect of the tread pattern is required. The results show that at a 95 percent confidence level, age is significant for all pavement surface types except DGAC. The estimated parameters indicate that the 1,000 Hz sound intensity increases with pavement age for all four mix types. Air-void content is not significant for all pavements. Surface layer thickness is significant for RAC-O pavements only. The estimated parameters indicate that a thicker RAC-O surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor only for DGAC and RAC-O pavements, and a higher MPD value corresponds to a higher noise level on DGAC pavements but to a lower noise level on RAC-O pavements. This explains why MPD is not a good estimator of surface smoothness, as it contains both negative and positive texture. Positive texture in DGAC gives rise to tire vibration and higher noise, whereas negative texture in RAC-O indicates a more porous material with a greater absorption effect and possibly a lower noise level.

The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise for any of the mixes. The number of high temperature days is only significant for RAC-G pavements, and with higher number of days with high temperature the sound level increases at the 1,000 Hz band.

Truck traffic volume is a significant factor that increases tire/pavement noise for OGAC and DGAC pavements. A higher traffic number results in a higher noise level at 1,000 Hz band. This higher noise level could be an indication of the lower durability of non-rubberized mixes.

A.4.3.5 Evaluation of Sound Intensity at the 2,000 Hz One-Third Octave Band

A.4.3.5.1 Descriptive Analysis

Figure A.16 shows the 2,000 Hz OBSI values observed in the six survey years on pavement sections of the four mix types. Generally, the 2,000 Hz sound intensity increases with pavement age. Newly paved surfaces with OGAC, RAC-G, and RAC-O mix types had significantly lower sound intensities at 2,000 Hz than dense-graded surfaces (DGAC).

Table A.36 shows the summary statistics and Figure A.26 shows the box plots of the 2,000 Hz OBSI band over six years for the different mix types in three age categories. As the figure shows, sound intensity generally increased with pavement age for the same pavement sections. The rate of increase in sound intensity with age at 2,000 Hz was lowest for the RAC-O pavements.

Figure A.27 shows the estimated cumulative distribution function of 2,000 Hz noise reduction for both the OGAC and RAC-O types of open-graded mixes and the RAC-G mixes compared to the average 2,000 Hz noise levels of DGAC mixes in six age groups. The average 2,000 Hz noise level on DGAC pavements, as shown in the legend, was approximately 88.9 dBA for newly paved overlays, between 90.0 and 90.2 dBA for pavements with ages between three and nine years, and approximately 91.1 dBA for pavements older than nine years.

A positive value in Figure A.27 indicates a reduction in noise levels compared to the average DGAC mix noise level. It is evident that the OGAC, RAC-G, and RAC-O pavements were all quieter than the DGAC pavements in terms of the 2,000 Hz band noise. With the exception of a few outliers, the noise reduction was generally between -2 dBA and 11 dBA for the OGAC pavements, between -2 dBA and 5 dBA for the RAC-G pavements, and between 0 dBA and 12 dBA for the RAC-O pavements.

For newly paved overlays (ages less than or equal to one year), the OGAC pavements had better noise-reducing properties than the other pavements, and could provide up to a 6 dBA noise-reduction benefit. In this age range, all the OGAC pavements, 80 percent of the RAC-O pavements, and 40 percent of the RAC-G pavements could provide noise reduction up to 3 dBA.

Table A.36: Summary Statistics for Sound Intensity at 2,000 Hz for All Mix Types

			Phase					
			1	**2**	**3**	**4**	**5**	**6**
Mix Type	DGAC	Valid N	15	13	8	6	8	5
		Mean	89.4	90.4	91.2	91.1	90.9	89.6
		Standard Deviation	1.5	1.9	1.1	.9	1.4	1.2
		Minimum	86.7	86.2	89.4	89.6	88.7	87.8
		Maximum	92.8	93.6	92.4	92.1	92.7	90.6
		Range	6.1	7.4	3.0	2.5	4.0	2.8
	OGAC	Valid N	15	17	17	13	17	12
		Mean	84.6	84.8	86.2	86.0	86.4	86.8
		Standard Deviation	1.9	2.1	1.8	1.9	3.3	1.2
		Minimum	80.9	82.0	82.3	82.5	78.3	85.0
		Maximum	87.7	89.3	89.0	89.0	91.1	88.8
		Range	6.8	7.3	6.7	6.5	12.8	3.8
	RAC-G	Valid N	13	12	9	10	8	4
		Mean	87.0	87.8	89.1	89.0	89.8	88.8
		Standard Deviation	1.8	1.2	1.5	1.4	1.2	.7
		Minimum	83.1	85.5	86.3	86.7	88.5	87.8
		Maximum	89.8	89.5	91.5	91.4	92.1	89.3
		Range	6.7	4.0	5.2	4.7	3.6	1.5
	RAC-O	Valid N	19	18	16	13	16	9
		Mean	84.8	85.0	86.5	85.8	85.7	85.8
		Standard Deviation	1.5	2.5	1.6	2.0	3.3	1.9
		Minimum	81.7	80.2	84.2	82.9	78.9	83.4
		Maximum	87.6	89.4	89.2	89.3	90.9	88.2
		Range	5.9	9.2	5.0	6.4	12.0	4.8

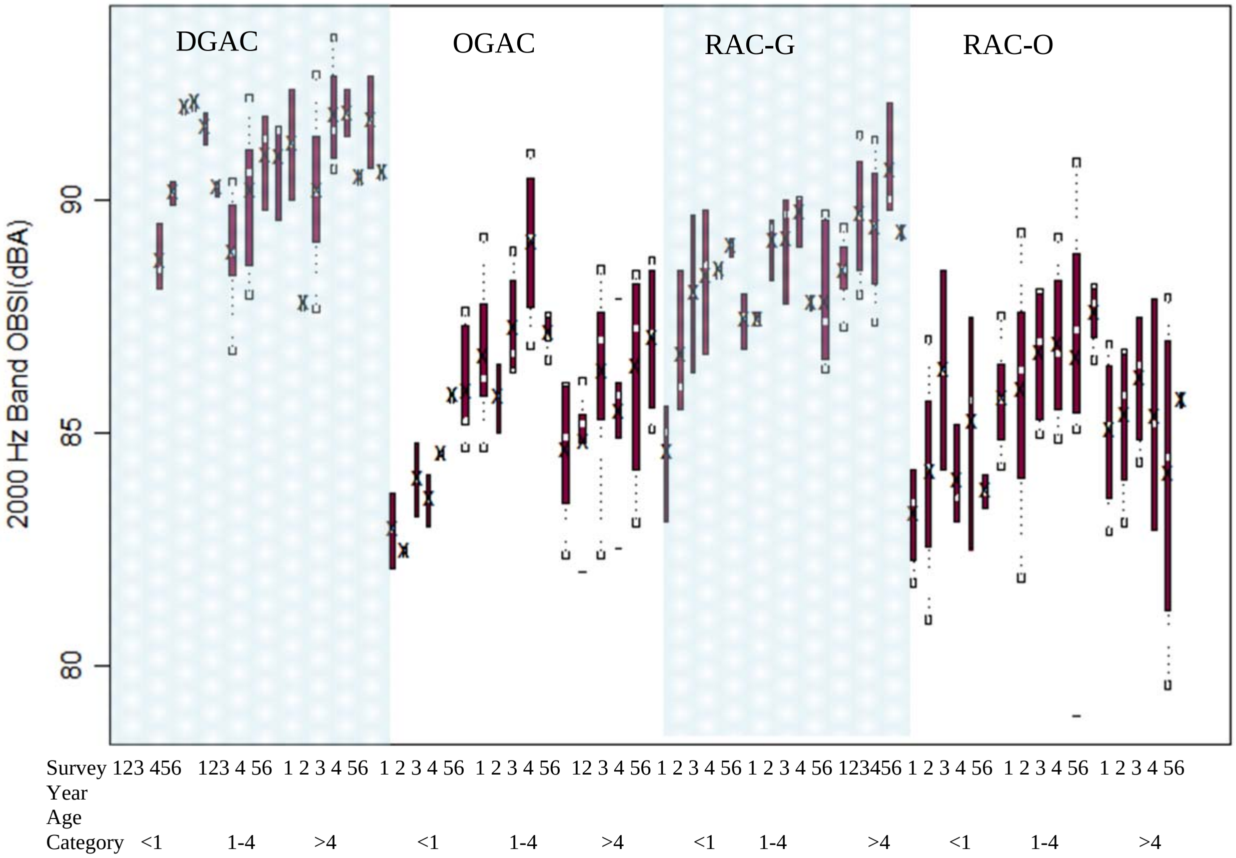


Figure A.26: Sound intensity at 2,000 Hz for different initial age categories (Age Category) for six years of data collection.

For the pavements with ages between one and three years, the OGAC and RAC-O pavements had very similar noise-reduction distributions—about 70 percent were at least 3 dBA quieter than the average DGAC pavement—while only 15 percent of RAC-G pavements were at least 3 dBA quieter than the average DGAC pavement. It is believed that RAC-G mixes in the sample were generally poorly compacted during construction and behaved similarly to the two types of open-graded mixes. They were then compacted by traffic in the wheelpath and therefore had lower air-void contents and were less able to reduce the air-pumping noise mechanism that is the dominant factor in high-frequency noise levels.

For the pavements with ages between three and nine years, the RAC-O and OGAC pavements seem to have similar performance, with about 50 percent of these sections having a noise level at least 3 dBA less than DGAC.

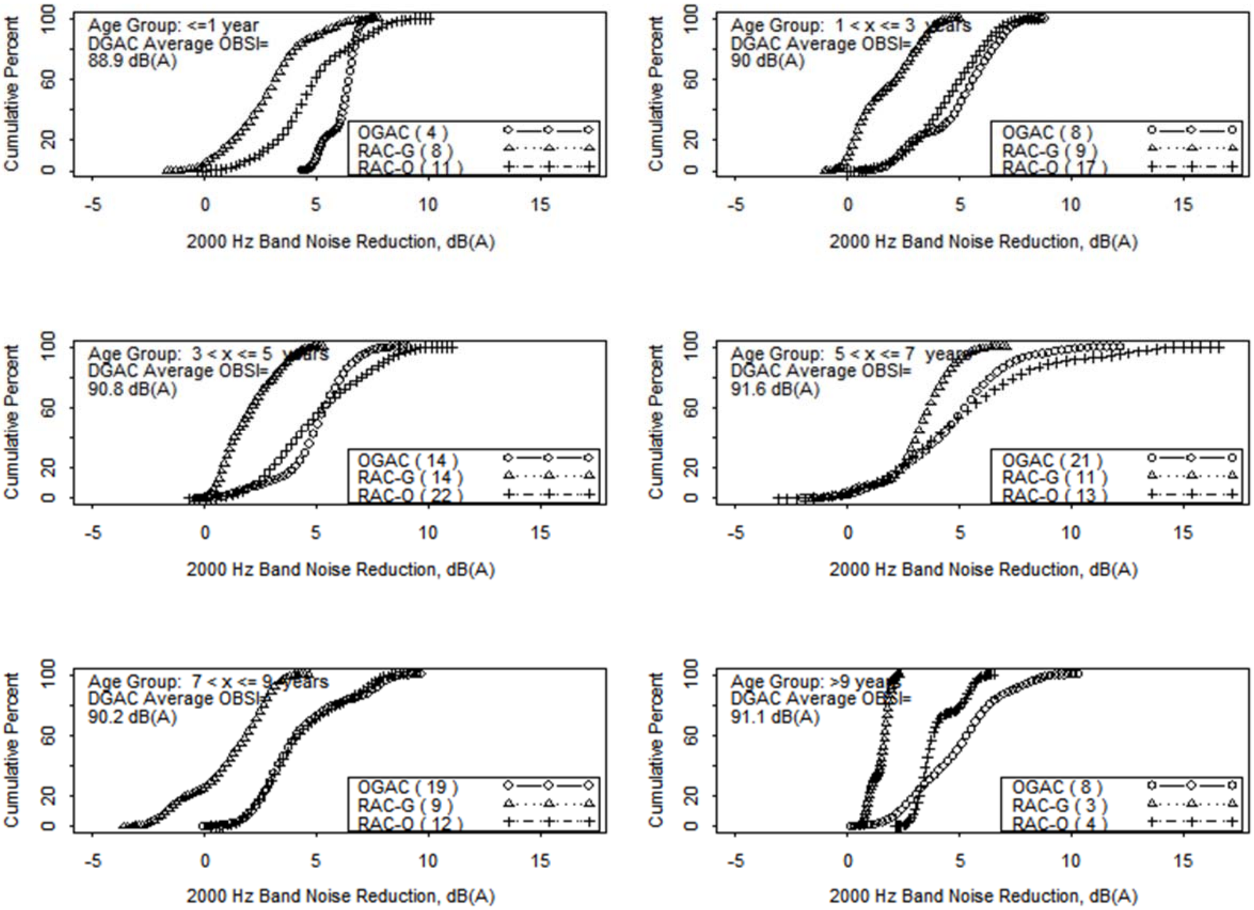


Figure A.27: Estimated cumulative distribution function of 2,000 Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: 1. A positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of the DGAC mixes in each age group.)

For the pavements older than nine years, all the pavement types had better performance than the DGAC, with OGAC having a broader range of noise reductions. About 40 percent of the pavements could provide up to a 6 dBA noise reduction. Nearly all of the OGAC and RAC-O pavements always provided at least 3 dBA of noise reduction in the 2,000 Hz band.

A.4.3.5.2 Statistical Analysis

Multiple regression analysis was conducted to account for the effects of different variables simultaneously. Two separate regression models were proposed. MPD was used as a surrogate for surface distresses such as raveling and rutting. In the first model, only the mix type (categorical variable) and environmental and traffic factors were included as independent variables, while the mix property variables were excluded. The regression equation appears as Equation A.5.17:

$$\begin{aligned}&2000Hz\ Sound\ Intensity(dBA)=89.5366+0.3077\times Age(year)-4.266\times ind(MixTypeOGAC)-1.8879\times ind(MixTypeRAC-G)\\&-4.0421\times ind(MixTypeRAC-O)+0.0021\times Thickness(mm)+0.0074\times NumberOfDays>30C\\&-0.0015\times MPD(micron)\end{aligned} \quad \textbf{(A.5.17)}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

Table A.37: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	89.1714	0.6893	129.3715	0
Age	**0.2554**	**0.0393**	**6.5041**	**0**
PvmntTypeOGAC	**-4.3113**	**0.4077**	**-10.5758**	**0**
PvmntTypeRAC-G	**-1.825**	**0.3767**	**-4.8441**	**0**
PvmntTypeRAC-O	**-4.3375**	**0.4101**	**-10.5762**	**0**
Thickness	0.0058	0.0076	0.7612	0.4473
NoDaysTempGT30	**0.006**	**0.0023**	**2.6639**	**0.0082**
AADTTCoringLane	0	0.0001	0.2595	0.7955
MPD	-0.001	0.0004	-2.8375	0.0049

Residual standard error: 1.681 on 226 degrees of freedom; Multiple R-Squared: 0.62.

At the 95 percent confidence level, age, mix type, MPD, and number of high temperature days significantly affect the 2,000 Hz sound intensity. The 2,000 Hz sound intensity increases with pavement age. The OGAC, RAC-G, and RAC-O pavement types all have lower initial 2,000 Hz sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for OGAC, RAC-G, and RAC-O mixes throughout the study are about 4.3 dBA, 1.8 dBA, and 4.3 dBA, respectively. Interestingly, MPD is a significant factor, with higher MPD values decreasing the sound level at the 2,000 Hz band. As discussed earlier, MPD is correlated with air-void content for open-graded mixes; as a result, higher air-void content will reduce the air-pumping effect and lower the sound level at 2,000 Hz, and texture may therefore appear significant because it is correlated with air-void content. It is therefore likely that the higher air-void content is responsible for the reduced noise. The interaction terms between age and mix type are not statistically significant, so they were not included in the model above. This indicates that the overall growth rate of 2,000 Hz sound intensity is not statistically different among the four pavement types.

In the second model, the mix type variable was replaced with the mix property variables and the model was estimated for each mix type separately. The regression equations appear as Equation A.5.18 through Equation A.5.21:

For DGAC pavements

$$\begin{aligned}&2000Hz\ Sound\ Intensity(dBA){=}93.9401\text{-}0.3671\times AirVoid(\%)+0.1488\times Age(year)-0.7015\times FinenessModulus\\&+0.0021\times MPD-0.0304\times Thickness(mm)+0.0031\times NumberOfDays>30C+0.0004\times AADTTinCoringLane\end{aligned} \quad \textbf{(A.5.18)}$$

Table A.38: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	93.9401	4.1408	22.6862	0
AirVoid	-0.3671	0.1853	-1.981	0.0623
Age	0.1488	0.0885	1.6807	0.1092
FinenessModulus	-0.7015	1.0208	-0.6872	0.5002
MPD	0.0021	0.0018	1.139	0.2688
Thickness	-0.0304	0.0154	-1.974	0.0631
NoDaysTempGT30	0.0031	0.0057	0.5388	0.5963
AADTTCoringLane	0.0004	0.0002	2.229	0.0381

Residual standard error: 1.154 on 19 degrees of freedom; Multiple R-Squared: 0.65.

For OGAC pavements

$$\begin{aligned}&2000Hz\ Sound\ Intensity(dBA){=}88.491\text{-}0.2527\times AirVoid(\%)+0.2287\times Age(year)-0.2199\times FinenessModulus-0.0006\times MPD(micron)\\&+0.0192\times Thickness(mm)-0.003\times NumberOfDays>30C-0.0007\times AADTTinCoringLane\end{aligned} \quad \textbf{(A.5.19)}$$

Table A.39: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	88.491	4.2361	20.8896	0
AirVoid	**-0.2527**	**0.1063**	**-2.3757**	**0.0237**
Age	**0.2287**	**0.0729**	**3.1371**	**0.0036**
FinenessModulus	-0.2199	1.0189	-0.2158	0.8305
MPD	0.0006	0.0005	1.1558	0.2563
Thickness	0.0192	0.019	1.0119	0.3192
NoDaysTempGT30	-0.003	0.0044	-0.6769	0.5033
AADTTCoringLane	**-0.0007**	**0.0002**	**-3.3373**	**0.0022**

Residual standard error: 1.121 on 32 degrees of freedom; Multiple R-Squared: 0.72.

For RAC-G pavements

$$2000Hz\ Sound\ \ Intensity(dBA)\text{=}81.0724\text{-}0.4368\times AirVoid(\%)+0.2721\times Age(year)+1.895\times FinenessModulus+0.0011\times MPD(micron) \\ -0.0411\times Thickness(mm)+0.0041\times NumberOfDays>30C+0.0006\times AADTTinCoringLane \qquad \textbf{(A.5.20)}$$

Table A.40: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	81.0724	5.1558	15.7244	0
AirVoid	**-0.4368**	**0.1156**	**-3.7782**	**0.001**
Age	**0.2721**	**0.0778**	**3.4983**	**0.002**
FinenessModulus	1.895	1.0961	1.7289	0.0978
MPD	0.0011	0.001	1.1751	0.2525
Thickness	**-0.0411**	**0.0163**	**-2.5159**	**0.0197**
NoDaysTempGT30	0.0041	0.0038	1.0978	0.2842
AADTTCoringLane	0.0006	0.0002	2.7677	0.0112

Residual standard error: 0.9872 on 22 degrees of freedom; Multiple R-Squared: 0.71.

For RAC-O pavements

$$2000Hz\ Sound\ \ Intensity(dBA)\text{=}112.124\text{-}0.1058\times AirVoid(\%)+0.3831\times Age(year)-5.0247\times FinenessModulus-0.0007\times MPD(micron) \\ -0.0077\times Thickness(mm)-0.0006\times NumberOfDays>30C+0.0003\times AADTTinCoringLane \qquad \textbf{(A.5.21)}$$

Table A.41: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	111.7392	6.308	17.714	0
AirVoid	-0.1103	0.0986	-1.1181	0.2707
Age	**0.3993**	**0.0742**	**5.3811**	**0**
FinenessModulus	**-4.9533**	**1.4173**	**-3.4949**	**0.0012**
MPD	-0.0009	0.001	-0.9308	0.358
Thickness	-0.0032	0.0227	-0.14	0.8894
NoDaysTempGT30	-0.0001	0.0041	-0.0304	0.9759
AADTTCoringLane	**0.0003**	**0.0001**	**2.936**	**0.0057**

Residual standard error: 1.094 on 37 degrees of freedom; Multiple R-Squared: 0.73.

Table A.42 summarizes the significant factors for each mix type.

Table A.42: Summary of Significant Factors for All Mixes for 2,000 Hz

	DGAC	OGAC	RAC-G	RAC-O
Air Void	✓*	✓	✓	
Age		✓	✓	✓
FinenessModulus			✓*	✓
MPD				
Thickness	✓*		✓	
NoDaysTempGT30				
AADTTCoringLane	✓	✓	✓	✓

*Significant at 10 percent significant level

Generally the R^2 are fairly high, around 0.7, for the open-graded mixes. The results of multiple linear regression analysis show that at the 95 percent confidence level, pavement age is not a significant factor for DGAC but it is for the other three mix types. The 2,000 Hz sound intensity decreases with increasing air-void content for all four mix types. Air-void content, however, is not a statistically significant factor for the RAC-O mixes. Older pavements have higher 2,000 Hz sound intensities, and age is a significant factor for all mixes except DGAC. Surface layer thickness is significant for RAC-G and DGAC pavements, and generally a thicker surface layer corresponds to a lower 2,000 Hz sound intensity for these pavements. Truck traffic volume is a significant factor that increases tire/pavement noise for all four mix types, signifying the effect of traffic in deteriorating the pavement surface. Macrotexture is not a contributing factor to high frequency noise, and the results of this analysis confirm that by showing that surface macrotexture (MPD) is not a significant variable for any of the mixes. Fineness modulus is only significant for RAC-O and RAC-G pavements: a higher fineness modulus results in a lower sound intensity at 2,000 Hz for open-graded mixes and a higher sound intensity for gap-graded mixes.

A.4.3.6: Evaluation of Sound Intensity at the 4,000 Hz One-Third Octave Band

A.4.3.6.1: Descriptive Analysis

Figure A.19 shows the 4,000 Hz OBSI values observed on each pavement section of the four mix types over the six survey years. Overall, it appears that 4,000 Hz sound intensity increases significantly with age only for RAC-G pavements. For DGAC pavements, the 4,000 Hz sound intensity increased slightly with age for newly paved overlays and remained constant for older sections too. On RAC-G pavements, the 4,000 Hz sound intensity increased with pavement age for both newly paved and older pavements. For OGAC pavements, the 4,000 Hz sound intensity increased with age only for newly paved overlays but tended to stabilize or even decrease slightly with age for pavements older than four years. For RAC-O pavements, the trend of 4,000 Hz sound intensity is unclear.

Figure A.28 and Table A.43 show the box plots and summary statistics, respectively, of the 4,000 Hz OBSI band over six years for the different mix types in three age categories. As the figure shows, 4,000 Hz band sound intensity generally increased with age for the same surface type. Newly overlaid OGAC, RAC-O, and RAC-G sections had significantly lower 4,000 Hz sound intensity values than DGAC sections. DGAC sections exhibited the lowest variability in 4,000 Hz sound intensity. For the DGAC and RAC-G mixes, the pavements that were older at the beginning of the study generally exhibited higher 4,000 Hz band sound intensity than the younger pavements. For the two open-graded mixes (OGAC and RAC-O), however, some of the pavements that were older at the start of the study exhibited lower 4,000 Hz band sound intensity than the younger pavements.

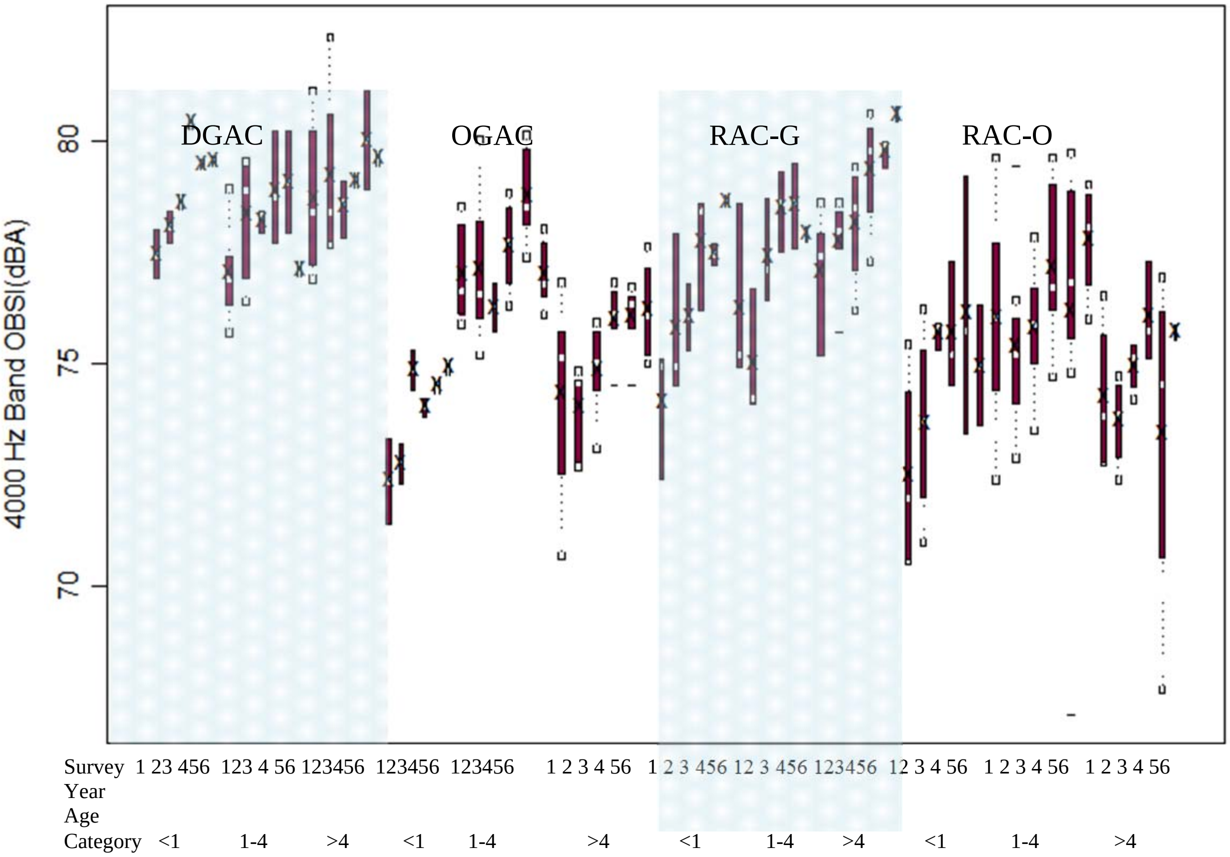


Figure A.28: Sound intensity at 4,000 Hz for different initial age categories (Age Category) and for six years of data collection.

Table A.43: Summary Statistics for Sound Intensity at 4,000 Hz for All Mix Types

			Phase					
			1	2	3	4	5	6
Mix Type	DGAC	Valid N	15.0	13.0	8.0	6.0	8.0	5.0
		Mean	77.8	78.3	78.3	79.4	79.2	79.3
		Standard Deviation	1.6	1.7	.4	1.1	1.0	1.3
		Minimum	75.6	75.4	77.8	77.7	77.9	77.1
		Maximum	81.2	82.4	79.1	80.4	81.1	80.6
		Range	5.6	7.0	1.3	2.7	3.2	3.5
	OGAC	Valid N	15.0	17.0	17.0	13.0	17.0	12.0
		Mean	75.0	74.5	75.5	76.4	75.9	76.4
		Standard Deviation	2.5	2.4	1.3	1.6	3.5	1.1
		Minimum	70.6	71.7	73.0	73.8	65.5	74.9
		Maximum	78.6	80.1	78.4	78.9	80.2	78.1
		Range	8.0	8.4	5.4	5.1	14.7	3.2
	RAC-G	Valid N	13.0	12.0	9.0	10.0	8.0	4.0
		Mean	76.2	76.6	77.4	78.6	78.7	79.0
		Standard Deviation	1.9	1.8	1.4	1.4	1.1	1.2
		Minimum	72.4	74.1	75.3	76.2	77.2	77.9
		Maximum	78.7	78.7	79.5	80.7	80.0	80.6
		Range	6.3	4.6	4.2	4.5	2.8	2.7
	RAC-O	Valid N	19.0	18.0	16.0	13.0	16.0	9.0
		Mean	74.5	74.2	75.6	76.5	75.5	76.3
		Standard Deviation	2.5	2.1	1.4	1.6	3.7	1.8
		Minimum	70.5	70.9	72.9	74.5	67.1	73.6
		Maximum	79.7	79.4	77.9	79.7	79.8	79.1
		Range	9.2	8.5	5.0	5.2	12.7	5.5

Figure A.29 demonstrates the estimated cumulative distribution function of 4,000 Hz noise reduction for OGAC, RAC-O, and RAC-G pavements compared to the average 4,000 Hz noise levels of DGAC pavements in six age groups. The average 4,000 Hz noise level on DGAC pavements, as shown in the figure legends, was about 77.2 dBA for newly paved overlays, between approximately 78.1 and 79.6 dBA for pavements with ages between three and nine years, and around 78.7 dBA for pavements older than nine years. The narrow range of sound intensities for the DGAC pavements indicates that the 4,000 Hz noise level on DGAC pavements did not change significantly with age.

A positive value in Figure A.29 indicates a reduction in noise levels compared to the average DGAC mix noise level. In general, the open-graded (OGAC and RAC-O) pavements were quieter than the DGAC pavements in the 4,000 Hz band noise level. The RAC-G pavements with ages between zero and seven years exhibited lower 4,000 Hz band noise compared to dense-graded mixes, but RAC-G pavements with ages greater than seven years exhibited similar or even higher 4,000 Hz band noise compared to DGAC pavements. Except for a few outliers, the noise reduction was generally between -3 dBA and 10 dBA for open-graded pavements, between -5 dBA and 10 dBA for RAC-O pavements, and between -5 dBA and 4 dBA for RAC-G pavements.

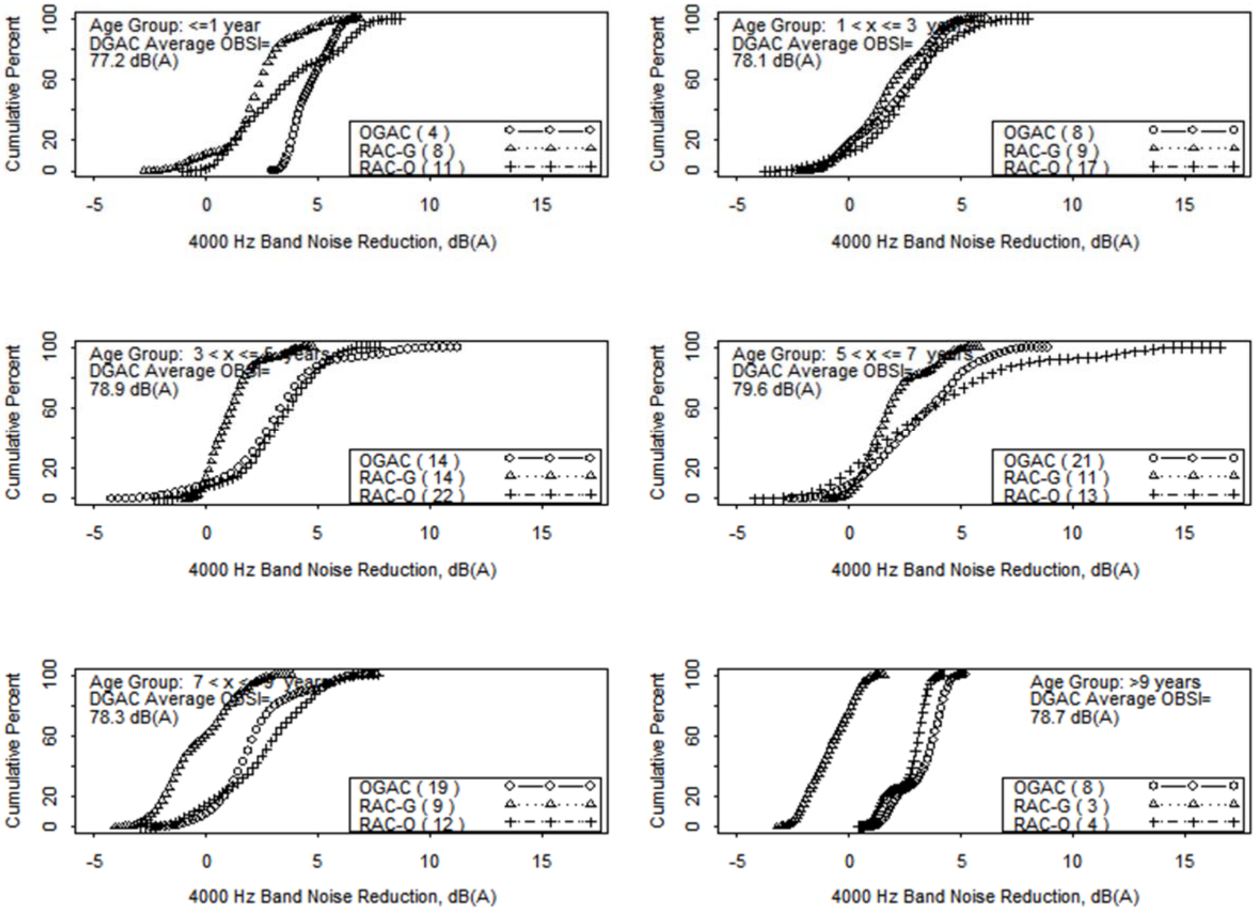


Figure A.29: Estimated cumulative distribution function of 4,000 Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: 1. A positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

For newly paved overlays, the RAC-G and RAC-O mix types exhibited similar noise-reducing properties, but the OGAC performed better than either of them, providing up to a 3 dBA noise reduction for nearly the entire population of the sample. For pavements with ages between one and three years, the OGAC, RAC-G, and

RAC-O exhibited very similar noise-reducing properties. Fifty percent of mixes could provide a 3 dBA noise reduction compared with DGAC. After three years the RAC-G pavements started showing signs of increased noise levels. Further, although RAC-G pavements with ages between three to five years had lost their noise-reducing capability, 50 percent of the OGAC and RAC-O pavements in that age category could still provide up to a 3 dBA noise reduction. RAC-O and OGAC pavements between seven and nine years old showed similar noise-reducing characteristics and were still better at noise reduction than the RAC-G pavements. RAC-O and OGAC pavements between seven and nine years old showed similar noise-reducing characteristics and were still better at noise reduction than the RAC-G pavements. From seven years and older, RAC-G mixes were generally noisier than DGAC mixes at the same age.

For pavements older than nine years, the OGAC and RAC-O mix types proved to be a better option than the other types as 60 percent of the sample population provided more than a 3 dBA noise reduction compared with similarly aged DGAC.

A.4.3.6.2 Statistical Analysis

Multiple regression analysis was conducted to account for the effects of various variables simultaneously. Two separate regression models were proposed. The models used MPD as a surrogate for surface distresses, primarily raveling. In the first model, only the mix type (categorical variable) and environmental and traffic factors were included as independent variables, while the mix property variables were excluded. The regression equation appears as Equation A.5.22:

$$\begin{aligned}&4000 Hz\ Sound\ \ Intensity(dBA) = 77.8702 + 0.1773 \times Age(year) - 1.8728 \times ind(MixTypeOGAC) - 2.1087 \times ind(MixTypeRAC - G)\\&-2.608 \times ind(MixTypeRAC - O) + 0.0166 \times Thickness(mm) + 0.004 \times NumberOfDays > 30C\\&+0.0004 \times AADTTinCoringLane - 0.0025 \times MPD(micron) + 0.1167 \times Age \times ind(MixTypeOGAC)\\&+0.3319 \times Age \times ind(MixTypeRAC - G) + 0.133 \times Age \times ind(MixTypeRAC - O)\end{aligned} \qquad \textbf{(A.5.22)}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

Table A.44: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	77.1529	0.739	104.3951	0
Age	0.1512	0.0724	2.0867	0.0379
PvmntTypeOGAC	**-2.224**	**0.7083**	**-3.14**	**0.0019**
PvmntTypeRAC-G	**-2.2995**	**0.6632**	**-3.4674**	**0.0006**
PvmntTypeRAC-O	**-2.5839**	**0.6548**	**-3.946**	**0.0001**
Thickness	**0.021**	**0.0075**	**2.7912**	**0.0057**
NoDaysTempGT30	0.0039	0.0022	1.7576	0.08
AADTTCoringLane	**0.0004**	**0.0001**	**4.8905**	**0**
MPD	**-0.0017**	**0.0004**	**-4.5833**	**0**
AgePvmntTypeOGAC	0.095	0.1029	0.9237	0.3565
AgePvmntTypeRAC-G	**0.3512**	**0.1064**	**3.3013**	**0.0011**
AgePvmntTypeRAC-O	0.037	0.1	0.3702	0.7116

Residual standard error: 1.818 on 254 degrees of freedom; Multiple R-Squared: 0.46.

At a 95 percent confidence level, age, pavement type, thickness, AADT in the coring lane, and MPD are significant. The 4,000 Hz sound intensity increases with pavement age. OGAC, RAC-G, and RAC-O all have lower 4,000 Hz sound intensity than DGAC. Compared to DGAC pavements, the average noise reductions for OGAC, RAC-G, and RAC-O mixes over the entire study are about 2.2 dBA, 2.3 dBA, and 2.6 dBA, respectively. Sound intensity at 4,000 Hz decreases as MPD increases. Moreover, MPD is generally correlated with air voids, and usually mixes with higher MPD will have higher air voids. Higher air-void content can reduce the air-pumping effect of a rolling tire, which mostly affects the noise level at high frequencies. The rate of increase in 4,000 Hz sound intensity for RAC-G is significantly higher than for the other three mixes. The 4,000 Hz sound intensity also increases with truck traffic volume and surface layer thickness.

In the second model, the mix type variable was replaced with the mix property variables and the model was estimated for each mix type separately. The regression equations appear as Equation A.5.23 through Equation A.5.26:

For DGAC pavements

$$\begin{aligned}&4000Hz\ Sound\ \ Intensity(dBA)\text{=82.4227-0.5099}\times AirVoid(\%)+0.1229\times Age(year)-0.3145\times FinenessModulus\\&+0.0007\times MPD-0.0342\times Thickness(mm)+0.0048\times NumberOfDays>30C+0.0004\times AADTTinCoringLane\end{aligned}\tag{A.5.23}$$

Table A.45: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	82.4227	3.426	24.058	0
AirVoid	**-0.5099**	**0.1533**	**-3.3256**	**0.0036**
Age	0.1229	0.0732	1.6772	0.1099
FinenessModulus	-0.3145	0.8446	-0.3724	0.7137
MPD	0.0007	0.0015	0.4508	0.6573
Thickness	**-0.0342**	**0.0127**	**-2.683**	**0.0147**
NoDaysTempGT30	0.0048	0.0047	1.0103	0.325
AADTTCoringLane	**0.0004**	**0.0001**	**2.9624**	**0.008**

Residual standard error: 0.955 on 19 degrees of freedom; Multiple R-Squared: 0.73.

For OGAC pavements

$$\begin{aligned}&4000Hz\ Sound\ \ Intensity(dBA)\text{=82.5643-0.2152}\times AirVoid(\%)+0.2123\times Age(year)-1.4211\times FinenessModulus-0.0003\times MPD(micron)\\&+0.0586\times Thickness(mm)-0.0044\times NumberOfDays>30C+0.0002\times AADTTinCoringLane\end{aligned}\tag{A.5.24}$$

Table A.46: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	82.5643	5.3369	15.4705	0
AirVoid	-0.2152	0.134	-1.6059	0.1181
Age	**0.2123**	**0.0918**	**2.3115**	**0.0274**
FinenessModulus	-1.4211	1.2837	-1.1071	0.2765
MPD	0.0003	0.0006	0.4513	0.6548
Thickness	**0.0586**	**0.0239**	**2.4484**	**0.02**
NoDaysTempGT30	-0.0044	0.0055	-0.8037	0.4275
AADTTCoringLane	0.0002	0.0003	0.7694	0.4473

Residual standard error: 1.413 on 32 degrees of freedom; Multiple R-Squared: 0.64.

For RAC-G pavements

$$\begin{aligned}&4000\mathit{Hz\ Sound\ Intensity}(\mathit{dBA})=74.5115\text{-}0.3061\times \mathit{AirVoid}(\%)+0.3928\times \mathit{Age}(\mathit{year})+0.6325\times \mathit{FinenessModulus}\\&+0.0012\times \mathit{MPD}(\mathit{micron})-0.0137\times \mathit{Thickness}(\mathit{mm})-0.0104\times \mathit{NumberOfDays}>30C+0.0007\times \mathit{AADTTinCoringLane}\end{aligned} \quad \textbf{(A.5.25)}$$

Table A.47: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	74.5115	6.9534	10.7159	0
AirVoid	-0.3061	0.1559	-1.9637	0.0623
Age	**0.3928**	**0.1049**	**3.7437**	**0.0011**
FinenessModulus	0.6325	1.4782	0.4279	0.6729
MPD	0.0012	0.0013	0.9018	0.3769
Thickness	-0.0137	0.022	-0.6229	0.5398
NoDaysTempGT30	-0.0104	0.0051	-2.0457	0.0529
AADTTCoringLane	**0.0007**	**0.0003**	**2.3027**	**0.0311**

Residual standard error: 1.331 on 22 degrees of freedom; Multiple R-Squared: 0.65.

For RAC-O pavements

$$\begin{aligned}&4000\mathit{Hz\ Sound\ Intensity}(\mathit{dBA})=102.3457\text{-}0.1405\times \mathit{AirVoid}(\%)+0.4201\times \mathit{Age}(\mathit{year})-5.2475\times \mathit{FinenessModulus}\\&-0.0017\times \mathit{MPD}(\mathit{micron})+0.0149\times \mathit{Thickness}(\mathit{mm})+0.0032\times \mathit{NumberOfDays}>30C+0.0008\times \mathit{AADTTinCoringLane}\end{aligned} \quad \textbf{(A.5.26)}$$

Table A.48: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	102.3457	6.2081	16.4858	0
AirVoid	-0.1405	0.0971	-1.4475	0.1562
Age	**0.4201**	**0.073**	**5.752**	**0**
FinenessModulus	**-5.2475**	**1.3948**	**-3.7621**	**0.0006**
MPD	-0.0017	0.001	-1.7488	0.0886
Thickness	0.0149	0.0223	0.6698	0.5071
NoDaysTempGT30	0.0032	0.004	0.8014	0.428
AADTTCoringLane	**0.0008**	**0.0001**	**7.9245**	**0**

Residual standard error: 1.076 on 37 degrees of freedom; Multiple R-Squared: 0.81.

Table A.49 summarizes the significant factors for each mix type.

Table A.49: Summary of Significant Factors for All Mixes at 4,000 Hz

	DGAC	OGAC	RAC-G	RAC-O
Air Void	✓		✓*	
Age		✓	✓	✓
FinenessModulus				✓
MPD				✓*
Thickness	✓	✓		
NoDaysTempGT30			✓*	
AADTTCoringLane	✓		✓	✓

*Significant at the 10 percent significance level

The results show that at a 95 percent confidence level, pavement age is a significant factor for the OGAC, RAC-O, and RAC-G pavements but not for DGAC. The estimated coefficients indicate that the 4,000 Hz sound intensity increases with pavement age. Truck traffic volume is a significant factor for all the pavement types except OGAC: higher traffic volume gives rise to a higher 4,000 Hz noise level. Air-void content is significant only for the DGAC and RAC-G mixes. Generally, higher air-void content decreases the 4,000 Hz sound intensity. The aggregate gradation variable (fineness modulus) does not appear to significantly affect tire/pavement noise on any pavement type except RAC-O. Higher fineness modulus leads a lower 4,000 Hz sound intensity. Pavement surface macrotexture (MPD) is not a significant factor for sound intensity at a 5 percent significance level. Thickness seems to have some effect on the measured noise level for non-rubberized pavements (DGAC and OGAC). An increase in thickness decreases the sound intensity at 4,000 Hz for DGAC pavements and increases the sound intensity for OGAC pavements at that frequency.

At 4,000 Hz, the number of days with temperature greater than 30°C is only significant for RAC-G pavements and at the 10 percent significance level, and an increase in the number of days with temperature higher than 30°C results in a decrease in the sound intensity at that frequency.

A.4.3.7: Sound Intensity at Other One-Third Octave Bands

A similar set of analyses showed that trends for sound intensities at other one-third octave bands in between those analyzed in detail here were similar to those of the adjacent frequency bands on either side of them in the spectrum. For this reason, only the trends and models for the 500 H, 1,000 H, 2,000 H, and 4,000 Hz frequencies have been discussed in this report. For more information on these other bands, see Appendix B.4.

A.4.4: Summary of Findings

The following findings were obtained regarding overall sound intensity:

1. Based on statistical analysis, for newly paved overlays, the overall sound intensities measured on OGAC, RAC-G, and RAC-O pavements were lower than the values measured on the DGAC pavements.
2. According to the model and not accounting for other variables, the average noise reductions (compared to DGAC pavements) for the OGAC, RAC-G, and RAC-O mixes over the lives of the test sections were approximately 3.5 dBA, 1.5 dBA, and 2.6 dBA, respectively. After the pavements were exposed to traffic, the overall sound intensity measured on RAC-G pavements rapidly increased, most likely due to postconstruction compaction from traffic, and became similar to what was measured on DGAC pavements of similar ages.
3. Based on the estimated trend of OGAC sound intensities, the overall sound intensity measured on the OGAC pavements is estimated not to change much for about six to eight years and then to increase at a faster rate with pavement age.
4. Based on the estimated trend of RAC-O sound intensities, the overall sound intensity measured on the RAC-O pavements is estimated not to change much for about ten years and then to increase at a faster rate with pavement age.
5. The ranking (from best to worst) of the four mix types in terms of overall noise reduction is RAC-O, OGAC, RAC-G, and DGAC.
6. Multiple regression analysis on all the mixes shows that overall sound intensity increases with pavement age for all the mix types but that age is only significant for the OGAC and RAC-O mixes. At the 95 percent confidence level, the in-situ permeability is a significant factor only for RAC-G pavements. The surface layer thickness is significant only for RAC-O, possibly due to the fact that for the other mix types the thicknesses were typically similar. Thicker RAC-O mixes produce lower overall noise levels than thinner ones. Pavement surface macrotexture (MPD) is a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. For OGAC and RAC-O pavements, MPD does not have a significant influence on noise level. For all the mix types, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. Truck traffic volume is a significant factor that increases tire/pavement noise for OGAC and DGAC mixes. The rubberized mixes are not as sensitive to truck traffic. For RAC-G mixes, the number of high temperature days per year is significant, and the estimated coefficient (0.0095) indicates that tire/pavement noise increases when the number of high temperature days increases.

The following findings were obtained regarding sound intensity at one-third octave bands:

1. For newly paved OGAC and RAC-O mixes, the sound intensities at the frequencies higher than 1,000 Hz remained relatively constant with age over the study, but the sound intensities at low frequencies (630 to

800 Hz) increased with age. The spectra show that for OGAC and RAC-O pavements, the sound intensities increased in all frequencies but more significantly for frequencies lower than 1,000 Hz.

2. For pavements between several years old and six to eight years old, sound intensity increased at slower rate across all frequencies.
3. For older pavements, the overall sound intensity with age for all mix types increased. The increase of sound intensity with age mainly occurred at frequencies between 1,000 Hz and 2,500 Hz for RAC-G and DGAC pavements, while for OGAC pavements the increase of sound intensity with age mainly occurred at frequencies below 1,000 Hz. RAC-O pavements did not exhibit a significant increase over the entire range of one-third octave frequencies which makes it a good treatment option for noise mitigation.
4. At low frequency noise (500 Hz and 630 Hz), sound intensities measured on OGAC and RAC-O pavements were generally higher than the values measured on DGAC and RAC-G pavements.
5. At a frequency level of 800 Hz, the sound intensities measured on OGAC, RAC-G, and RAC-O pavements became lower than those measured on DGAC pavements, with RAC-O having the lowest measured sound intensity. For frequency levels equal to or over 1,000 Hz, the sound intensities measured on RAC-G pavements were generally lower than those measured on DGAC pavements. Generally, RAC-O and OGAC pavements exhibited a lower sound intensity for frequencies greater than 1,000 Hz.

The following findings were obtained regarding 500 Hz band sound intensity:

1. For newly paved sections, 500 Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) are generally higher than the values measured on dense- or gap-graded pavements (DGAC and RAC-G). For pavements with an age between four and seven years, there seems to be no significant difference in 500 Hz sound intensity levels among four mixes. For old pavements (more than seven years), OGAC pavements seem to have higher 500 Hz sound intensity than the other three pavement types proving that OGAV pavements are more susceptible to surface distresses.
2. Sound intensity generally increases with pavement age for each mix type. Overall, the rate of sound intensity increase is lower on rubberized pavements (RAC-G and RAC-O) than on non-rubberized pavements (DGAC and OGAC). Old open graded (>4) appear to reach to a terminal value for noise.
3. The average 500 Hz noise level on DGAC pavements, is about 85.7 dBA for newly paved overlays, between 86.6 and 88.7 dBA for pavements with an age between three and nine years, and approximately 90.3 dBA for pavements older than nine years.
4. For newly paved overlays (age less than or equal to one year old), RAC-G pavements seem to have 500 Hz noise levels similar to DGAC pavements. About 40 percent of the pavements with RAC-G mix on them are quieter than DGAC. The open-graded pavements are significantly noisier than the DGAC pavements.
5. For pavements with an age more than nine years, both RAC-G and RAC-O mixes have similar noise characteristics and provide about 3 dBA noise reduction over DGAC. OGAC pavements are on average

2 dBA noisier than DGAC pavements. Table A.22 tabulates a summary statistics for sound intensity at 500Hz frequency.

6. Multiple regression analysis at the 5 percent significance level indicated that, age, number of high temperature days, truck traffic in the coring lane, and MPD significantly affect the 500 Hz band sound intensity. Only OGAC pavements exhibit a significant difference from DGAC mixes. The 500 Hz sound intensity increases with pavement age, truck traffic volume, and MPD, but decreases with number of high temperature days. The growth rate of overall sound intensity is not statistically different among the four pavement types.
7. Multiple regression analysis on individual mix type shows that age is not a significant factor for any of the pavement types for noise at 500 Hz except OGAC at the 95 percent confidence level. Truck traffic volume is a significant factor that contributes to the increase of the 500 Hz band noise for open-graded mixes and gap-graded mixes but not dense graded mixes. Among the four mix types, air-void content is statistically significant at the 95 percent confidence level only for OGAC and DGAC pavements. The estimated coefficient indicates that higher air-void content is correlated with noise at the 500 Hz band noise, although this is probably not a causal relationship. For OGAC pavements, the aggregate gradation variable (fineness modulus) significantly affects the low-frequency noise. The number of high temperature days is a statistically significant variable for open graded mixes. More high temperature days tend to result in lower low-frequency noise on OGAC and RAC-O pavements at this frequency. For DGAC, RAC-G, and RAC-O pavements, MPD is a statistically significant variable. A higher MPD value (i.e., higher macrotexture) increases tire vibration and tends to increase low-frequency noise. For RAC-G mixes thickness is significant at ten percent confidence level and thicker pavements produce lower noise compared to thin pavements.

The following findings were obtained regarding 1,000 Hz band sound intensities:

1. For newly paved overlays, the 1,000 Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC G) are lower than the values measured on dense-graded pavements (DGAC). Sound intensity at 1,000 Hz is a function of both tire vibration and the air pumping effect, and is mainly affected by tire tread pattern and not pavement characteristics.
2. The rate of increase of sound intensity is the lowest on RAC-O pavements, which indicates that RAC-O pavements retain their noise-reducing properties over a longer period.
3. The average 1,000 Hz noise level on DGAC pavements is approximately 95.6 dBA for newly paved overlays, between approximately 95.9 and 97.3 dBA for pavements with an age between three and nine years, and approximately 97.5 dBA for pavements older than nine years. Except for pavements older than nine years, OGAC and RAC-O pavements are all generally quieter than the DGAC pavements in terms of 1,000 Hz band noise. Between 10 to 30 percent of middle age (between 3 to 9 years old) RAC-G pavements produce louder noise than dense grade mixes.

4. Multiple regression analysis on all mixes shows that age, mix type, number of high temperature days, and layer thickness significantly affect the 1,000 Hz band sound intensity. The 1,000 Hz band noise increases with pavement age and number of high temperature days, but decreases with layer thickness.
5. For newly paved overlays (age less than or equal to one year), OGAC and RAC-G pavements have similar noise-reducing properties, with both showing noise reductions of 3 dBA or more compared to DGAC for about 20 percent of the sections. RAC-O pavements reduce noise more effectively than OGAC and RAC-G. About 10 percent of OGAC and 20 percent of RAC-G pavements are noise-reducing if noise reduction is defined as 3dBA or more reduction, but about 50 percent of RAC-O pavements are noise-reducing compared with DGAC of the same age for this frequency.
6. Small sample size of pavements older than nine years old suggest that only a small portion of OGAC pavements still perform well and provide satisfactory noise characteristics compared to DGAC pavements. Hence, the rank of the three mixes from best to worst is RAC-O, RAC-G, and OGAC.
7. Multiple regression analysis at the 95 percent confidence level, show that 1,000 Hz sound intensity level is affected by several factors such as age, mix type, surface layer thickness, and number of high temperature days significantly. The 1,000 Hz sound intensity increases with pavement age and the temperature, but decreases with the surface layer thickness. Among the three pavement types, OGAC, RAC G, and RAC-O, all have lower initial 1,000 Hz sound intensity than DGAC. The average noise reductions compared to DGAC pavements for newly paved OGAC, RAC-G, and RAC-O mixes are about 3.3, 1.5, and 4.7 dBA, respectively. The overall growth rate of 1,000 Hz sound intensity is not statistically different among the four pavement types.
8. Multiple regression analysis on individual mix type shows, likely due to the unseen effects of tire tread dominating the noise, all regression equations have low R^2 values (around 0.50). The results show that at a 95 percent confidence level, age is significant for all pavement surface types except DGAC. The estimated parameters indicate that the 1,000 Hz sound intensity increases with pavement age for all four mix types. Air-void content is not significant for all pavements. Surface layer thickness is significant only for RAC-O pavements. The estimated parameters indicate that a thicker RAC-O surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor only for DGAC and RAC-O pavements, and a higher MPD value corresponds to a higher noise level on DGAC pavements, but to a lower noise level on RAC-O pavements. Positive texture in DGAC gives rise to tire vibration and higher noise, whereas negative texture in RAC-O indicates a more porous material with more damping effect and possibly lower noise level. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise for all mixes. Number of high temperature days is only significant for RAC-G pavements, and with higher number of days with high temperature the sound level increases at 1,000 Hz. Truck traffic volume is a significant factor that increases tire/pavement noise for OGAC and DGAC pavements. A higher number for annual truck traffic results in higher noise level at 1,000 Hz.

The following findings were obtained regarding the 2,000 band sound intensities:

1. The average 2,000 Hz noise level on DGAC pavements was approximately 88.9 dBA for newly paved overlays, between 90.0 and 90.2 dBA for pavements with ages between three and nine years, and approximately 91.1 dBA for pavements older than nine years. For all pavement types, the 4,000 Hz sound intensity of newly paved sections increased with age. For initially older sections, however, the rate of increase with age in high frequency sound intensity was more pronounced for RAC-G sections. OGAC, RAC-G, and RAC-O pavements were all quieter than the DGAC pavements in terms of 2,000 Hz band noise. The noise reduction over the entire set of measurements was generally between -2 and 11 dBA for open-graded pavements, between -2 and 5 dBA for RAC-G pavements, and between 0 and 12 dBA for RAC-O pavements.
2. For newly paved overlays (age less than or equal to one year), OGAC pavements had better noise-reducing properties than other pavements, and could provide up to a 6 dBA noise-reducing benefit. In this age range all OGAC pavements, 80 percent of RAC-O pavements, and 40 percent of RAC-G pavements could provide up to a 3 dBA noise reduction compared with DGAC. For pavements older than nine years, all pavement types had better performance than DGAC, with OGAC being the best. About 40 percent of the OGAC pavements could provide up to a 6 dBA noise benefit. Almost all of the RAC-O pavements always provided at least 3 dBA noise reduction in the 2,000 Hz band.
3. Multiple regression analysis for all mixes combined at the 95 percent confidence level showed that age, mix type, MPD, and number of high temperature days significantly affect the 2,000 Hz sound intensity. The 2,000 Hz sound intensity increases with pavement age. OGAC, RAC-G, and RAC-O all have lower initial 2,000 Hz sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 4.3 dBA, 1.8 dBA, and 4.3 dBA, respectively. Interestingly, MPD is a significant factor and higher MPD values decrease the sound level at 2,000 Hz. The overall growth rate of 2,000 Hz sound intensity is not statistically different among the four pavement types.
4. Multiple regression analysis on individual mix type shows that generally the R^2 are fairly high around 0.7 for the open-graded mixes. Pavement age is a significant factor for all mix types except DGAC. 2,000 Hz sound intensity decreases with the increase of air-void content for all four mix types. Air-void content, however, is not a statistically significant factor for RAC-O mixes. Older pavements have higher 2,000 Hz sound intensities and age is a significant factor for all mixes except DGAC. The surface layer thickness is significant for RAC-G and DGAC pavements. Generally, a thicker surface layer corresponds to a lower 2,000 Hz sound intensity for these pavements. Truck traffic volume is a significant factor that increases tire/pavement noise for all four mix types. Macrotexture is not a contributing factor on high frequency noise and the results of the analysis confirms that as surface macrotexture (MPD) is not a significant variable for any of the mixes. Fineness modulus is only significant for RAC-O and RAC-G pavements. A higher

fineness modulus results in a lower sound intensity at 2,000 Hz for open-graded mixes and higher sound intensity for gap-graded mixes.

The following findings were obtained regarding the 4,000 band sound intensities:

1. 4,000 Hz sound intensity increased significantly with age only for RAC-G pavements. For DGAC pavements, the 4,000 Hz sound intensity increased slightly with age for newly paved overlays and remained constant for initially older sections, as well. On RAC-G pavements, the 4,000 Hz sound intensity increased with pavement age for both newly paved and older pavements. For OGAC pavements, the 4,000 Hz sound intensity increased with age only for newly paved overlays but flattened or even decreased slightly with age for pavements older than four years. For RAC-O pavements, the 4,000 Hz sound intensity trend was not clear.
2. 4,000 Hz band sound intensity generally increased with age on the same pavement section. Newly overlaid OGAC, RAC-O, and RAC-G sections had significantly lower 4,000 Hz sound intensity values than DGAC sections. DGAC sections exhibited the lowest variability in 4,000 Hz sound intensity. For DGAC and RAC-G mixes, older pavements generally exhibited higher 4,000 Hz band sound intensity than younger pavements. For the two open-graded mixes (OGAC and RAC-O), however, older pavements sometimes exhibited lower 4,000 Hz band sound intensity than younger pavements.
3. The average 4,000 Hz noise level on DGAC pavements was about 77.2 dBA for newly paved overlays, between approximately 78.1 and 79.6 dBA for pavements with ages between three and nine years, and around 78.7 dBA for pavements older than nine years.
4. For newly paved overlays, RAC-G, RAC-O, and OGAC all generally exhibited noise-reducing properties compared to DGAC of the same age, with OGAC performing better than the other two mix types by providing up to a 3 dBA noise reduction for all sections in that age category. Of the pavements that were more than nine years old, the OGAC and RAC-O pavements were absolutely a better option than other pavement types and 60 percent of the time could provide more than a 3 dBA noise reduction.
5. Multiple regression analysis for all mixes combined at a 95 percent confidence level shows that age, pavement type, thickness, AADT in the coring lane, and MPD are significant factors. The 4,000 Hz sound intensity increases with pavement age. OGAC, RAC-G, and RAC-O all have lower initial 4,000 Hz sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 2.2 dBA, 2.3 dBA, and 2.6 dBA, respectively. Sound intensity at 4,000 Hz decreases as MPD increases. Among all mix types, the rate of increase in 4,000 Hz sound intensity for RAC-G is significantly higher than all other mixes. The 4,000 Hz sound intensity also increases with truck traffic volume and surface layer thickness.
6. Multiple regression analysis on individual mix type at a 95 percent confidence level shows that pavement age is a significant factor for all the pavements except DGAC. The estimated coefficients indicate that the 4,000 Hz sound intensity increases with pavement age. Truck traffic volume is a significant factor for all the

pavement types except OGAC: Higher traffic volume causes a higher 4,000 Hz noise level. Air-void content is significant only for DGAC and RAC-G mixes. Generally, higher air-void content decreases the 4,000 Hz sound intensity. The aggregate gradation variable (fineness modulus) does not significantly affect tire/pavement noise on any pavement type except RAC-O. Higher fineness modulus results in a lower 4,000 Hz sound intensity. Pavement surface macrotexture (MPD) is not a significant factor for sound intensity at the five percent significance level. Pavement thickness has some effect on the measured noise level for nonrubberized pavements (DGAC and OGAC). An increase in thickness decreases the sound intensity at 4,000 Hz for DGAC pavements and increases the sound intensity at 4,000 Hz for OGAC pavements.

A.5: Environmental Sections Analysis

Some of the so-called “Environmental Sections” (ES sections) were revisited during the six-year survey. This appendix subsection presents an analysis of the performance trends of the different mixes at each site.

A.5.1 Fresno 33 Sections

The Fresno 33 site includes nine test sections with five different surfacing mixes—RAC-G, Type G-MB, Type D-MB, RUMAC-GG, and DGAC—in the northbound direction of State Route 33 near the town of Firebaugh in Caltrans District 6. Except for the DGAC control surface, all the sections were placed with both 45 and 90 mm thicknesses. The mixtures used in all sections have a nominal maximum aggregate size (NMAS) of 19 mm. The test sections were one year old during the first-year measurements. All the gap-graded mixes had the same aggregate gradations; the DGAC mix had a slightly finer dense gradation than the Type D-MB mix. The MB mixes generally had lower stiffness than the other mix types at 20°C, and the DGAC mix had the highest stiffness. These sections were not revisited in the sixth year of data collection.

A.5.2 Sacramento 5 and San Mateo 280 Sections

The Sacramento 5 and San Mateo 280 sites consist of thin RAC-O overlays placed on jointed PCC. The overlay thickness on the Sacramento 5 sections (which have the same overlay in two directions of travel) is approximately 30 mm and on the San Mateo 280 section it is 40 mm. Over the first five years of data collection, the Sacramento 5 site was evaluated in both the northbound (NB) and southbound (SB) directions, while the San Mateo 280 section was only evaluated in the northbound direction. At the time of the first year of measurements, the Sacramento 5 sections were one year old and the San Mateo section was three years old. Both sites have an NMAS of 12.5 mm. Neither of these sections was revisited for the sixth year of data collection.

A.5.3 LA 138 Sections

The LA 138 site includes four mix types—OGAC, RAC-O, Bituminous Wearing Course (BWC), and DGAC—that were placed in eastbound and westbound lanes. Over the first five years of data collection, measurements were taken on seven test sections: on the eastbound (EB) and westbound (WB) OGAC, RAC-O, and BWC sections, and on the westbound DGAC mix. In the sixth year of data collection one eastbound section and one westbound section were dropped from the experimental design because they had undergone maintenance. All the mixes at this site have an NMAS of 12.5 mm, and all the test sections were three years old during the first-year measurements. OGAC was placed in 75 mm and 30 mm thicknesses on different sections so the effect of thickness on noise and roughness could be determined. All the other sections were placed at a thickness of 30 mm.

Roughness and noise for the different mixes were collected over the six years and then analyzed to compare the different mixes and thicknesses. The analysis helps answer these questions:

- Does thickness affect noise levels and roughness?
- How did the performance of the open-graded and BWC mixes compare to the performance of the DGAC mix on the control section? It must be noted that the BWC mix at this site is not considered by industry to be representative of most other BWC mixes in the state.

It is worthwhile mentioning that the analysis of the first two years of data revealed that most of the LA 138 open-graded mixes had much lower than typical air-void contents compared to other OGAC mixes in the state. The permeability of these OGAC and RAC-O mixes was also lower than the average permeability of other OGAC and RAC-O mixes in the same age categories. The eastbound sections had higher air-void content and permeability values than the westbound sections, which may be due to compaction differences during construction as well as to the difference in truck traffic volumes in the two directions *(1, 6).*

Figure A.30 shows the six-year IRI values for the LA 138 sections. Of all the mixes, RAC-O had the lowest IRI values in the sixth year. In the first year of measurements, almost all the sections provided “good” ride quality, according to the FHWA criterion for non-interstate highways (i.e., less than 1.50 m/km [95 in./mi]) *(1).* For Years 5 and 6, there was a significant change in IRI for the OGAC mixes, and it appears that the thin OGAC mixes exhibited a greater change in IRI level compared to the thick OGAC layers. A slight change in IRI from Year 5 to Year 6 can be seen for the RAC-O and DGAC mixes.

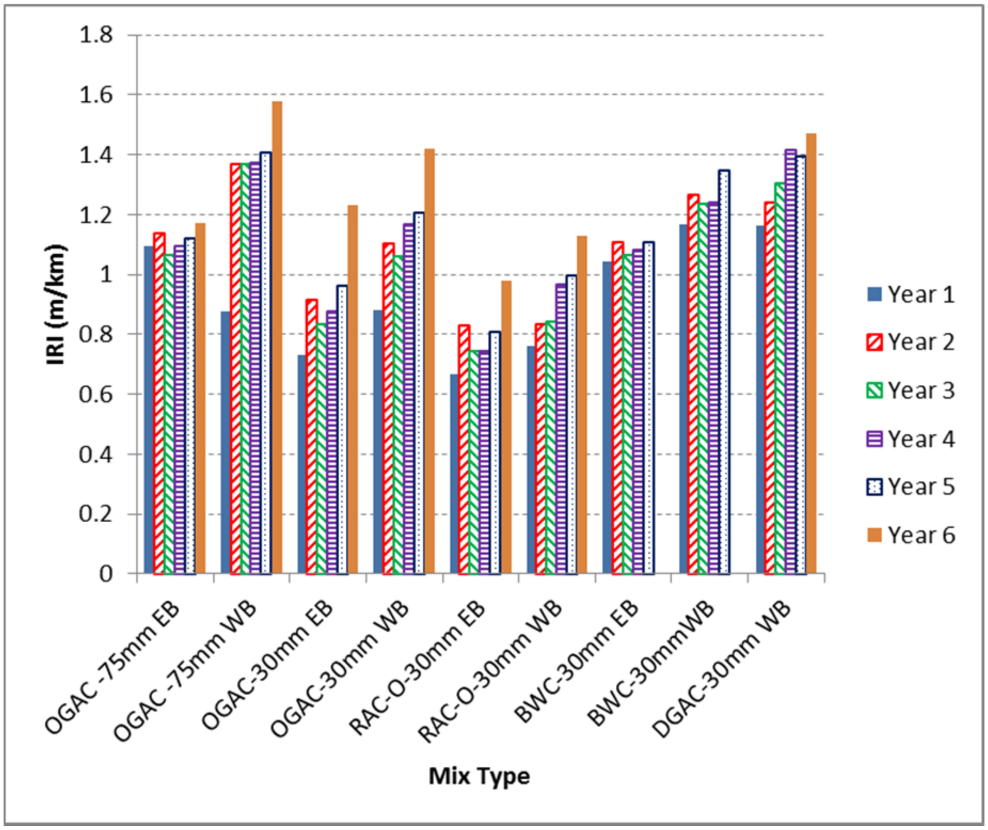


Figure A.30: Six-year IRI values for the LA 138 sections.
(Note: 1 m/km = 63 in/mi)

MPD was not measured on the LA 138 sections in the third-year. Results from the previous two years of measurement, which can be seen in Figure A.31, showed that open-graded mixes had higher MPD values than dense-graded mixes (*1, 6*). The RAC-O mixes exhibited smaller MPD values than the OGAC pavements. In the fifth year, MPD decreased significantly for all the sections. The reason for the decrease in the MPD value from Year 4 to Year 5 is unknown. A slight change in MPD between Years 5 and 6 was observed but this has been attributed to random measurement error. There seems to be no interaction between layer thickness and the change in the MPD.

Figure A.32 shows the six-year overall sound intensity levels for the LA 138 sections. There are errors in the third-year measurements on the DGAC and westbound BWC sections, so the data for these two sections was excluded *(1, 6)*. In the sixth year of data collection, the overall OBSI sound intensity remained constant or slightly decreased for RAC-O and the open-graded mixes, whereas the sound intensity of the dense-graded mixes increased. Open-graded mixes, including the OGAC with 30 mm and 75 mm thicknesses, and the RAC-O exhibited a lower overall sound intensity level than the DGAC sections, with a measured overall sound intensity of about 104 dBA. The sound intensity spectra, as shown in Figure A.33, revealed that in the sixth year the noise levels in the high-frequency bands (1,000 Hz to 5,000 Hz) were slightly lower than those in the fifth year, and noise levels in the low-frequency bands (500 Hz to 1000 Hz) were slightly higher than those in the fifth year. This indicates that in the sixth year the pavement surface experienced a change in air-void content that resulted in more noise due to air pumping and some surface raveling, resulting in higher noise level at lower frequency range.

There was no interaction observed between surface layer thickness and overall sound intensity.

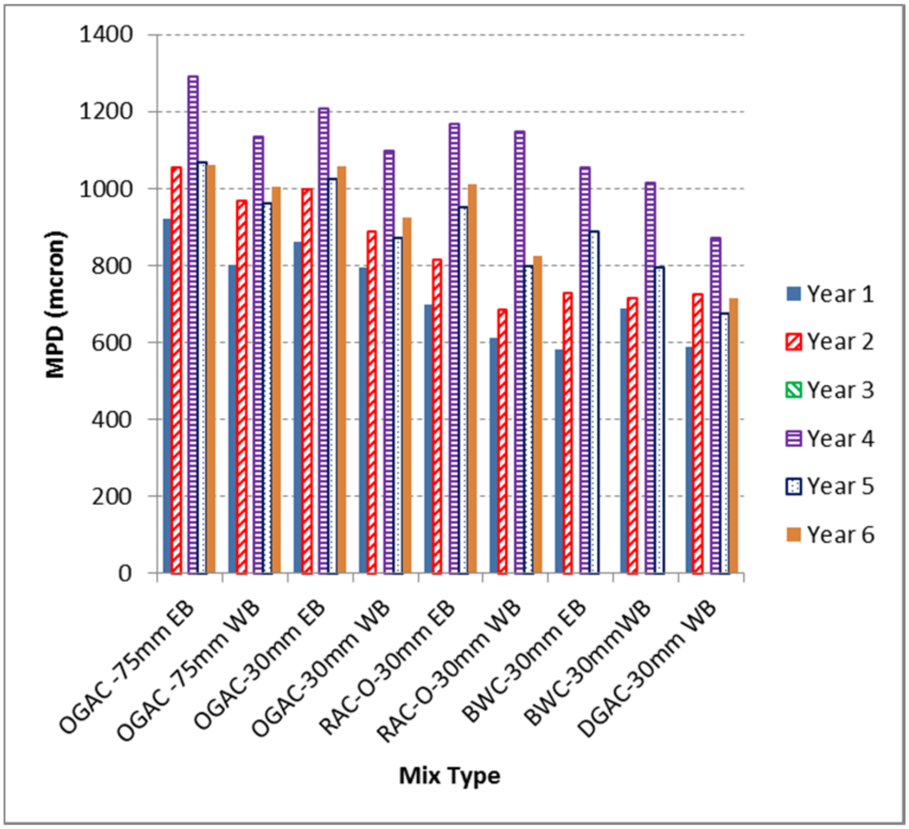


Figure A.31: Six-year MPD values for the LA 138 sections.

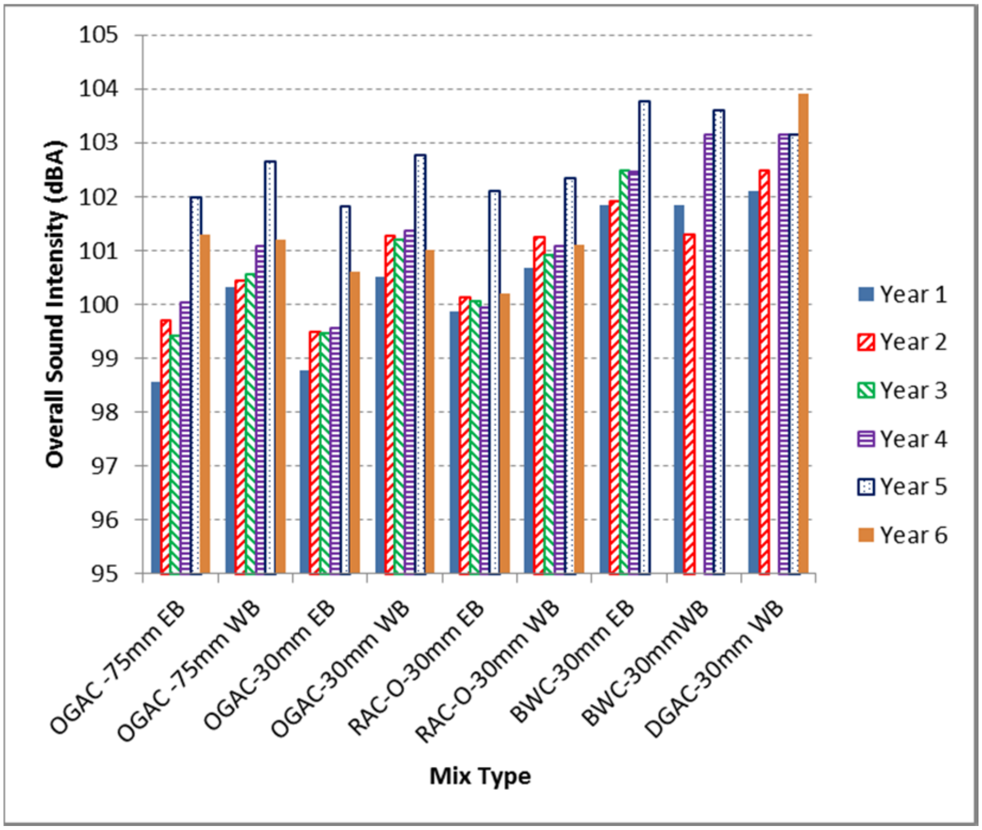


Figure A.32: Six-year overall OBSI values for LA 138 sections.

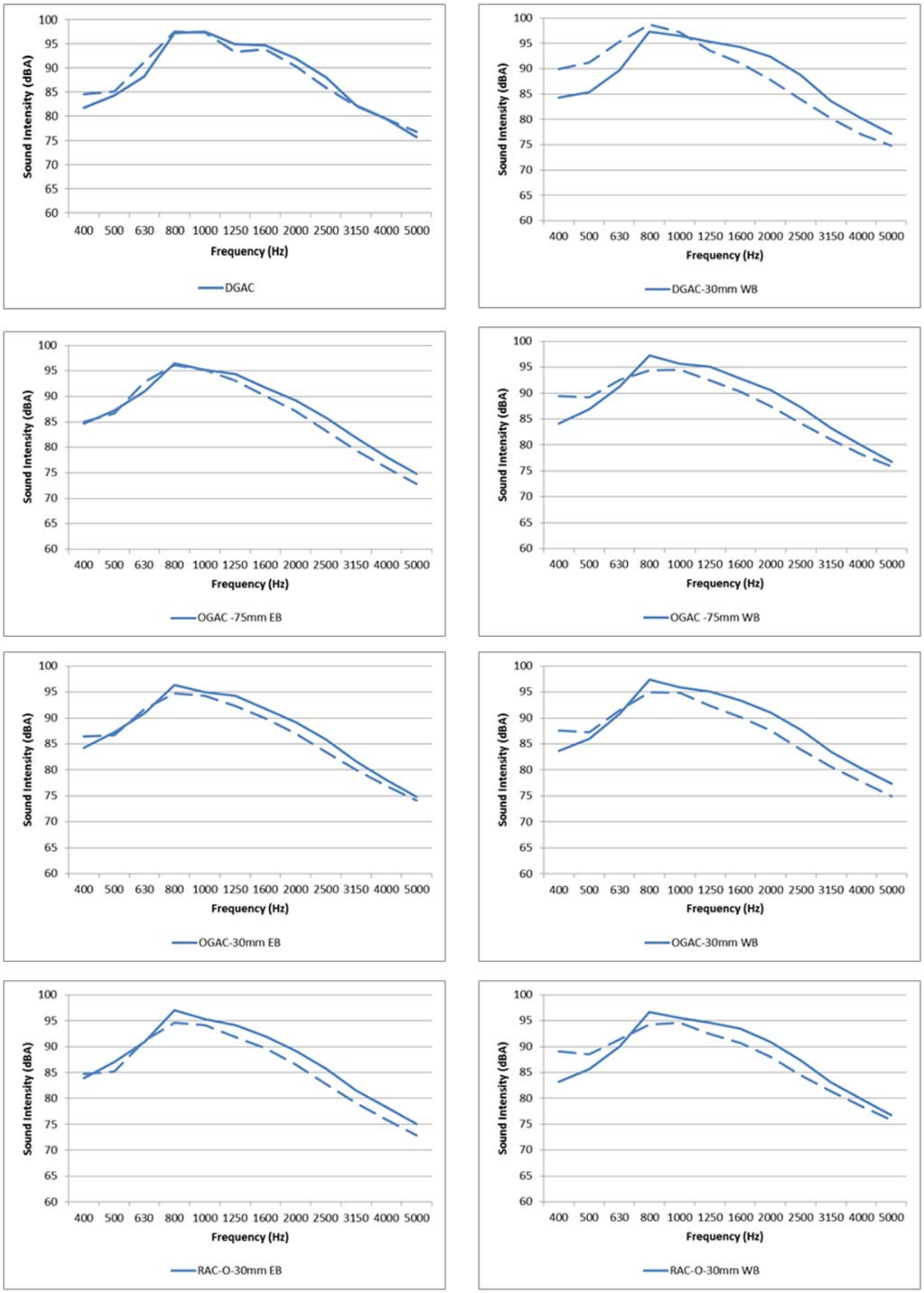


Figure A.33: Frequency differences between Year 5 and Year 6 for the LA 138 sections. (Solid lines show fifth year and dashed lines show the sixth year.)

In summary, among the LA 138 sections, the RAC-O mixes had the lowest noise levels among all the mix types across the six survey years.

A.5.4 LA 19 Sections

The LA 19 section has a European gap-graded (EU-GG) mix as a surface layer. It was less than a year old when the first-year measurements were conducted in this study *(1,* 6*).* This section was not revisited in the sixth year because there was no control section and there were no other sections of this type to form a sufficient data set to reach conclusions about this mix type.

A.5.5 Yolo 80 Section

The Yolo 80 section has a 20 mm OGAC surface layer. It was seven years old in the first year of measurements. The first two years of data collection showed that this section had higher air-void content but lower permeability than the average OGAC mix *(1).*

Figure A.34 shows the six-year IRI values for the Yolo 80 section. The figure shows that the IRI values increased significantly from Year 5 to Year 6. However, the section can still provide good ride quality for interstate highways according to the FHWA guideline (less than 1.50 m/km [95 in./mi]) *(1).*

Figure A.35 shows the six-year MPD values for the Yolo 80 section. After an initial increase in MPD, the values remained constant for the next four years. This change in MPD values is not statistically significant, and can be attributed to random error in measurement.

Figure A.36 shows the six-year overall noise levels for the Yolo 80 section. In the first two years this section had an overall sound intensity from between 102 dBA and 103 dBA that increased to slightly over 105 dBA by the sixth year. The noise spectrum of this section, which appears in Figure A.37, shows increases in noise mainly occurring at frequencies lower than 1,000 Hz in the early years, indicating that the increase was probably caused by raveling, and at frequencies above 1,000 Hz in Year 5 and Year 6, indicating that the surface permeability was decreasing.

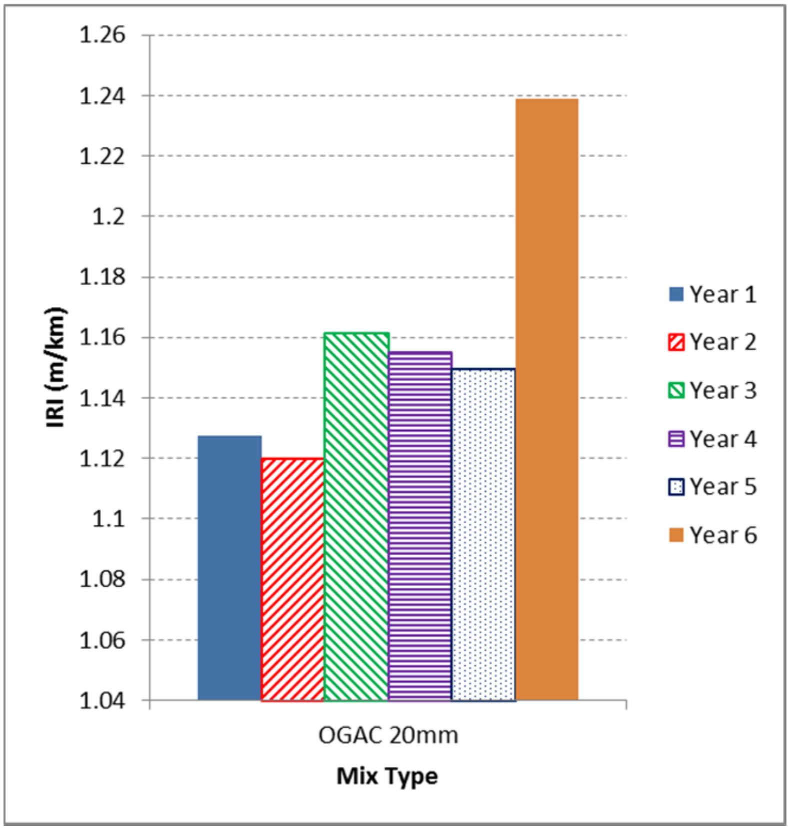


Figure A.34: Six-year IRI values for the Yolo 80 section.
(Note: 1 m/km = 63 in/mi)

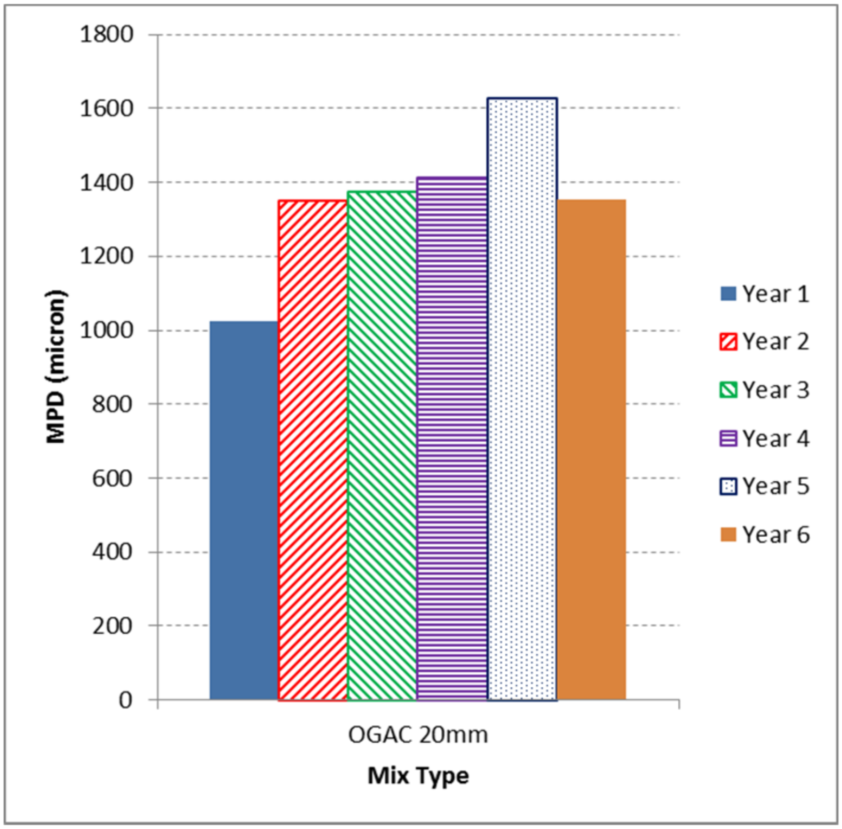


Figure A.35: Six-year MPD values for the Yolo 80 section.

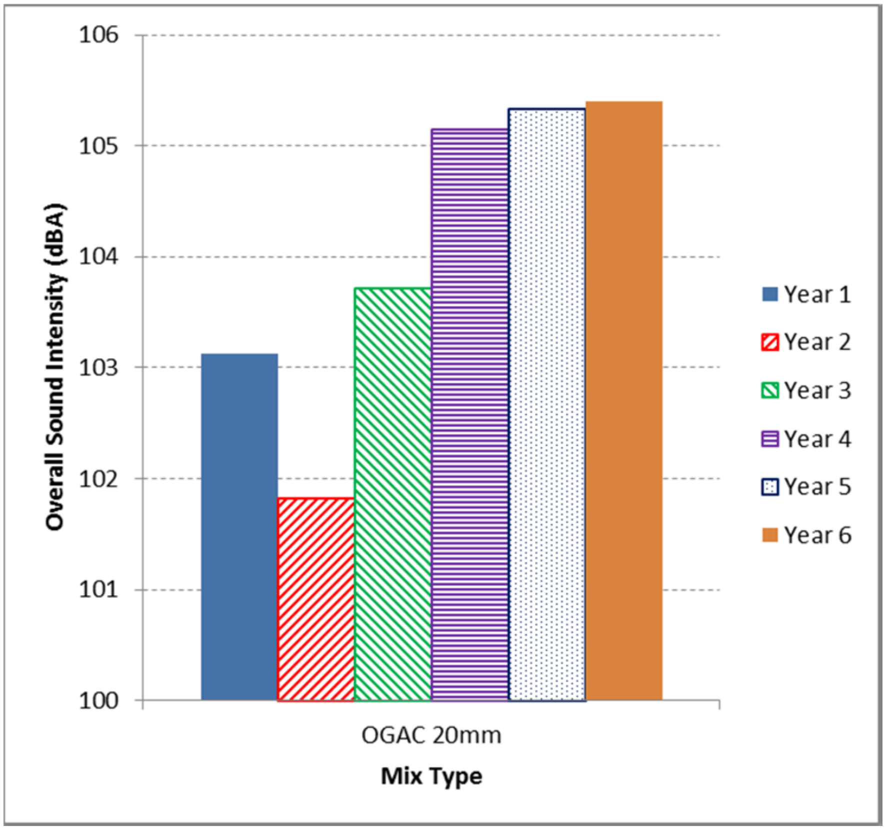


Figure A.36: Six-year overall OBSI values for the Yolo 80 section.

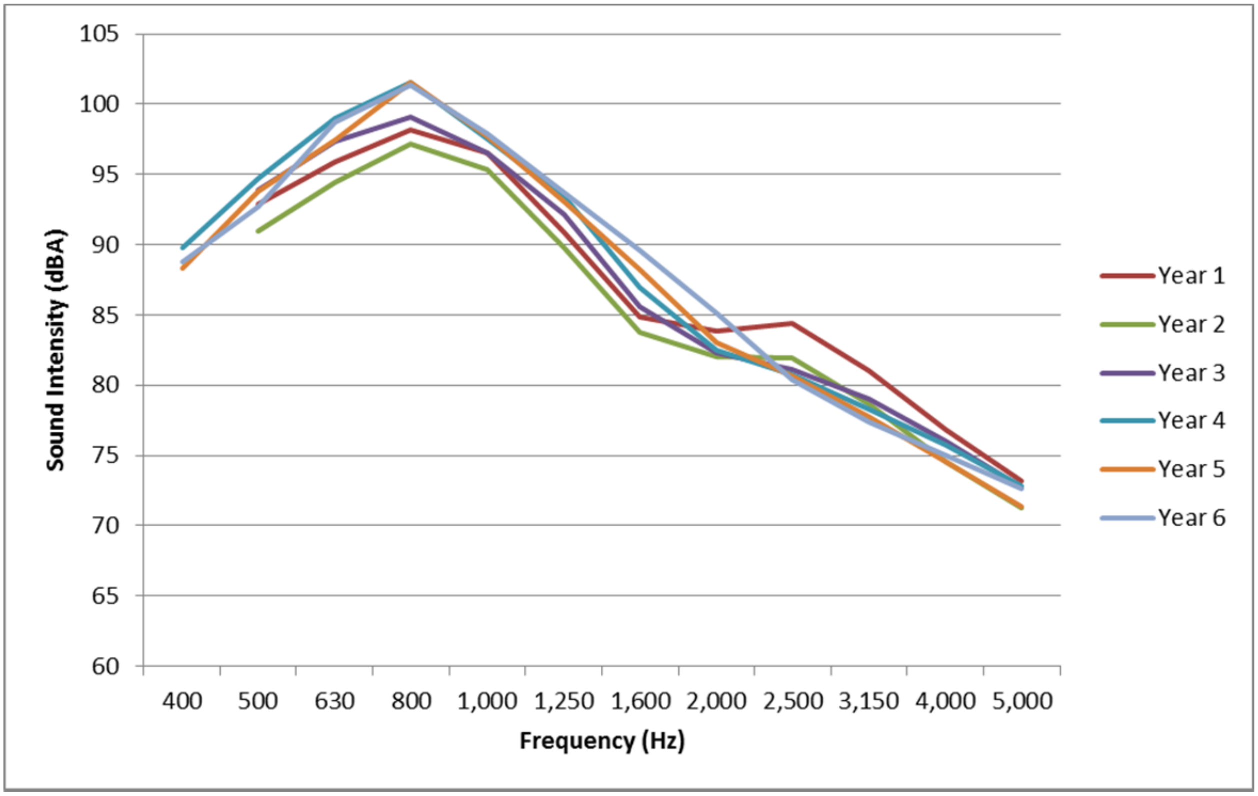


Figure A.37: Six-year one-third octave band frequency OBSI values for the Yolo 80 section.

In summary, the Yolo 80 section still provides acceptable ride quality after ten years in service, but it has a noise level close to that of DGAC pavements.

A.5.6 BWC Sections

To provide additional data regarding BWC, a set of eight sections at five different locations was tested with the UCPRC vehicle in July 2007, June 2011, and June 2012. Testing on the sections was conducted at 60 mph (97 km/h), except on Section BWC-01 where the speed was 35 mph (56 km/h). Because of this difference in test speed, this section was dropped from the experimental design and from the ensuing analysis.

Table A.50: BWC Section Locations

Section ID	Direction	Location	Section Name
BWC-01	–	04NAP-AmCanyon-W	American Canyon Rd
BWC-02	N	06KER99N5.4	Kern 99
	S	06KER99S5.4	
BWC-03	–	10SJO5N4.5	I-5
BWC-04	N	01MEN101N78.5	Laytonville
	S	01MEN101S78.5	
BWC-05	E	05MON156E2.0	Castroville
	W	05MON156W2.0	

No traffic closures were used for these sections, nor was there coring, permeability testing, or friction testing. The physical properties of some of these sections were obtained from the product manufacturer, SemMaterials, and are presented in Table A.51.

Table A.51: Physical Properties of BWC Sections from Data Provided by SemMaterials and from UCPRC OBSI Measurements

Section ID		NMAS	Construction Year	Type	Comment
BWC-01		9.5 mm	2007	BWC-G	Gap-graded bonded wearing course
BWC-02	N		2006	BWC-G PM	BWC gap-graded polymer-modified
	S			RBWC-O	RBWC Type O rubber mix
BWC-03			2005	RBWC-O	5/8 in. thick. First rubber-bonded wearing course rubber project in California (built in 2005)
BWC-04	N		2006	BWC-O PM	Open-graded mix over open-graded mix
	S				
BWC-05	E	9.5 mm	2005	BWC-G PM	
	W	9.5 mm	2005		

The overall sound intensity levels for each test section are presented in Figure A.38. Most of the sections exhibited an increase of 2 dBA over a four-year measurement interval, and they remained the same from Year 5 to Year 6, except for the BWC-04-N and BWC-04-S sections, which showed OBSI values about 6 dBA higher after four years. Figure A.39 indicates that the increase in the sound intensity of the BWC mixes occurred in both low and high frequency bands.

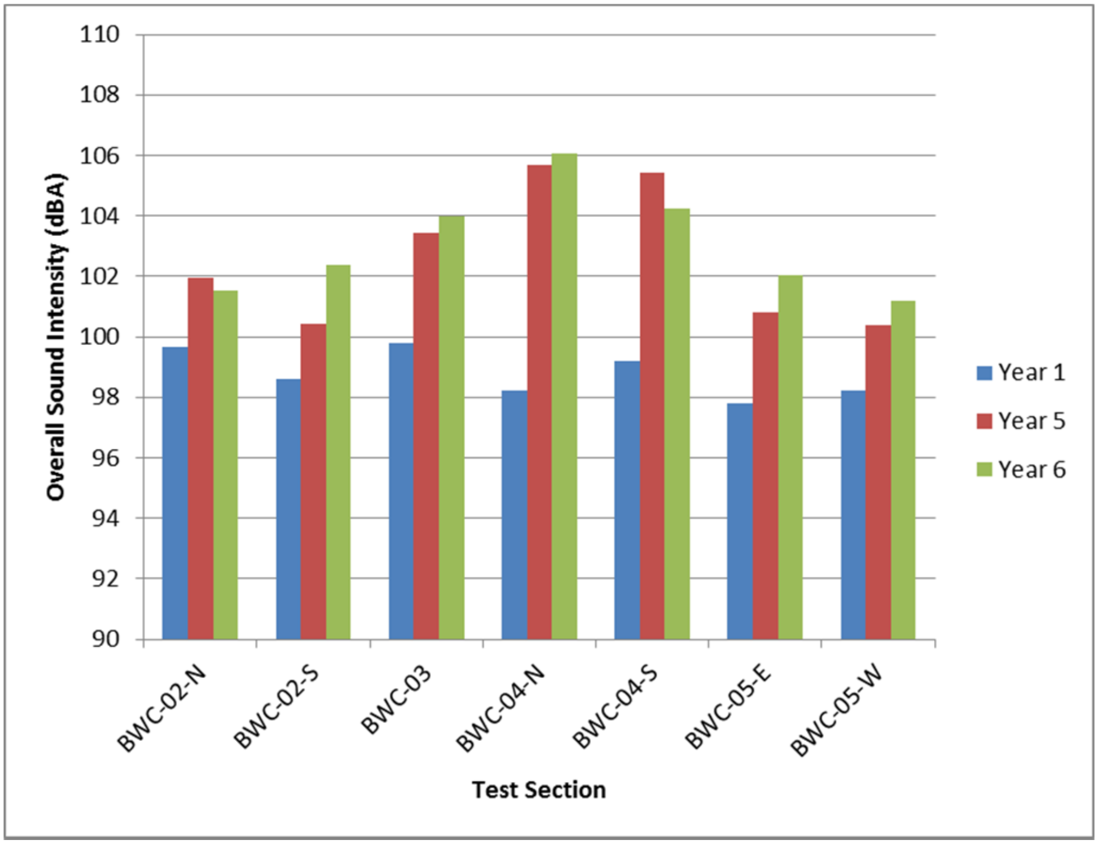


Figure A.38: Overall sound intensity levels of the BWC sections.

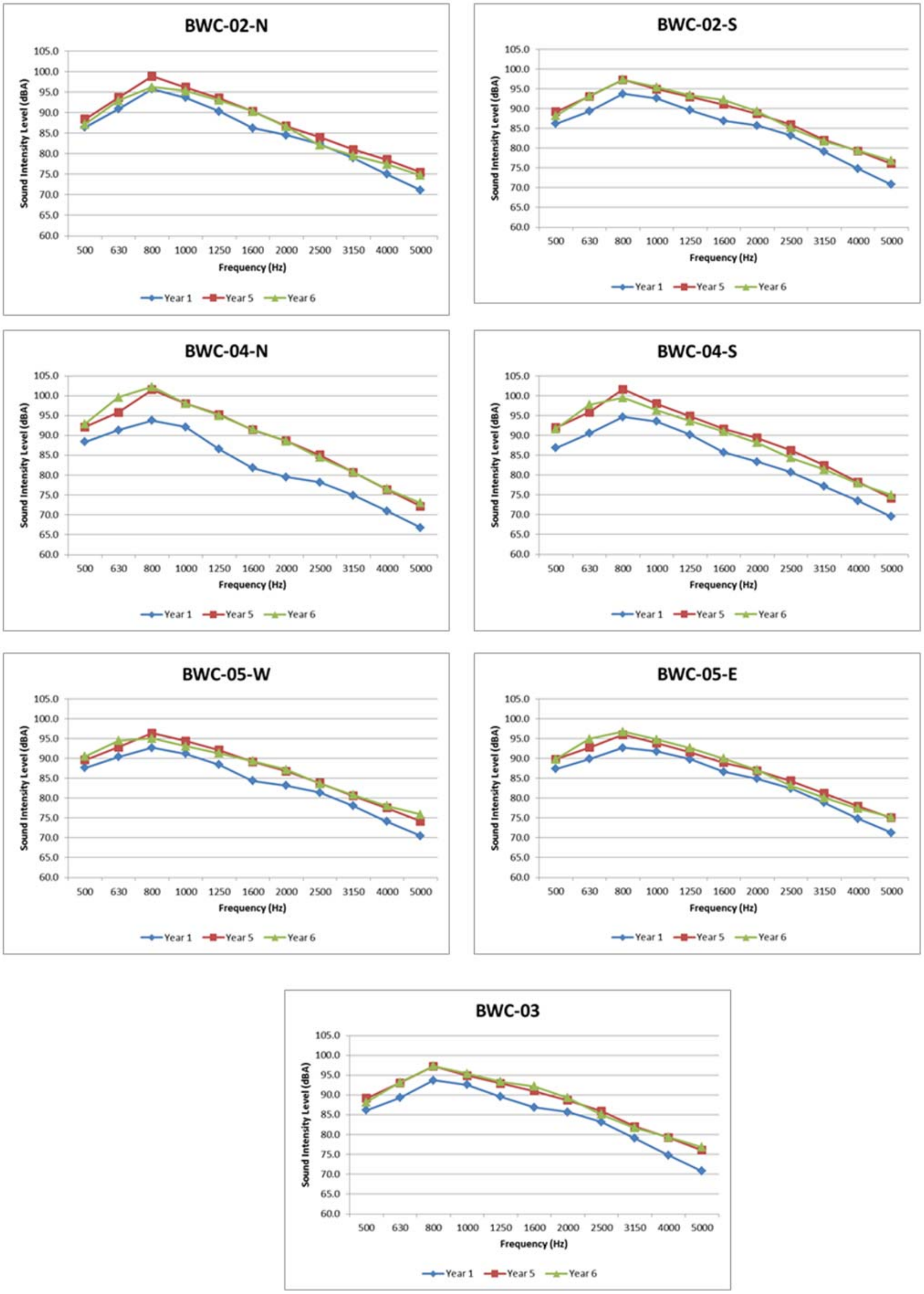


Figure A.39: One-third octave band sound intensity levels for the BWC sections.

Figure A.40, Figure A.41, and Figure A.42 compare the OBSI levels of these BWC sections with the DGAC in the QP and ES pavement sections measured in the different phases of data collection in 2007, 2011, and 2012, respectively. These figures show that in the first round of measurements, the BWC sections exhibited significantly lower overall sound intensity levels than their DGAC counterparts. In the second and third rounds of measurements, however, not only was there no noise-reduction benefit exhibited by the BWC sections, but the open-graded mix placed over an open-graded mix actually showed worse performance than conventional DGAC mixes.

International Roughness Index (IRI) was also obtained from elevation profiles measured on both wheelpaths, with the results for each section shown in Figure A.43. The right wheelpath measurements in the first year were believed to be erroneous so that data has not been shown in this figure. In general, sections BWC-04-N and BWC-04-S had the highest IRI values. The IRI change for almost all of the sections over six years was not significant.

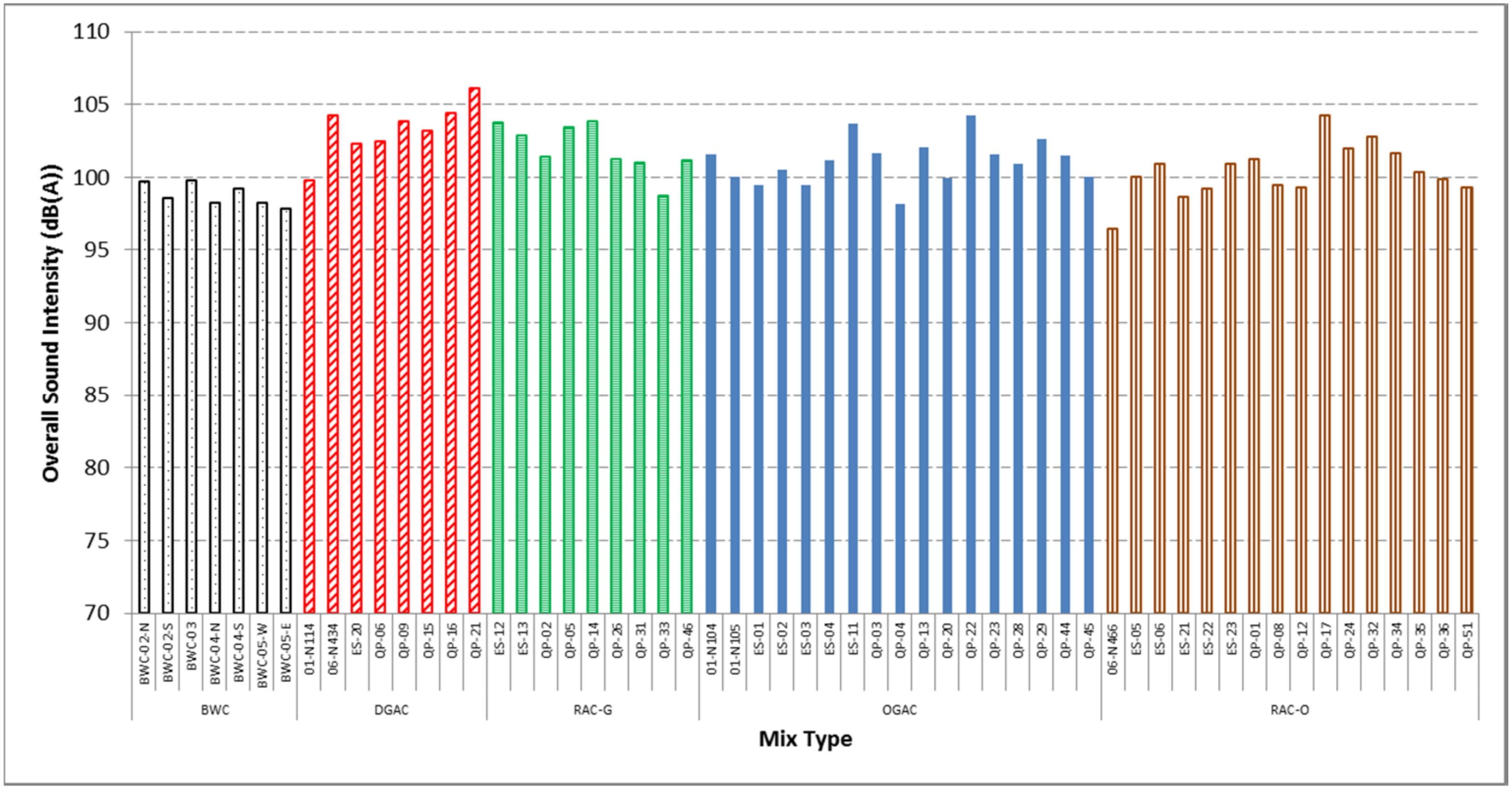


Figure A.40: Sound intensity levels of BWC compared to other pavement types, first round of measurements, 2007.

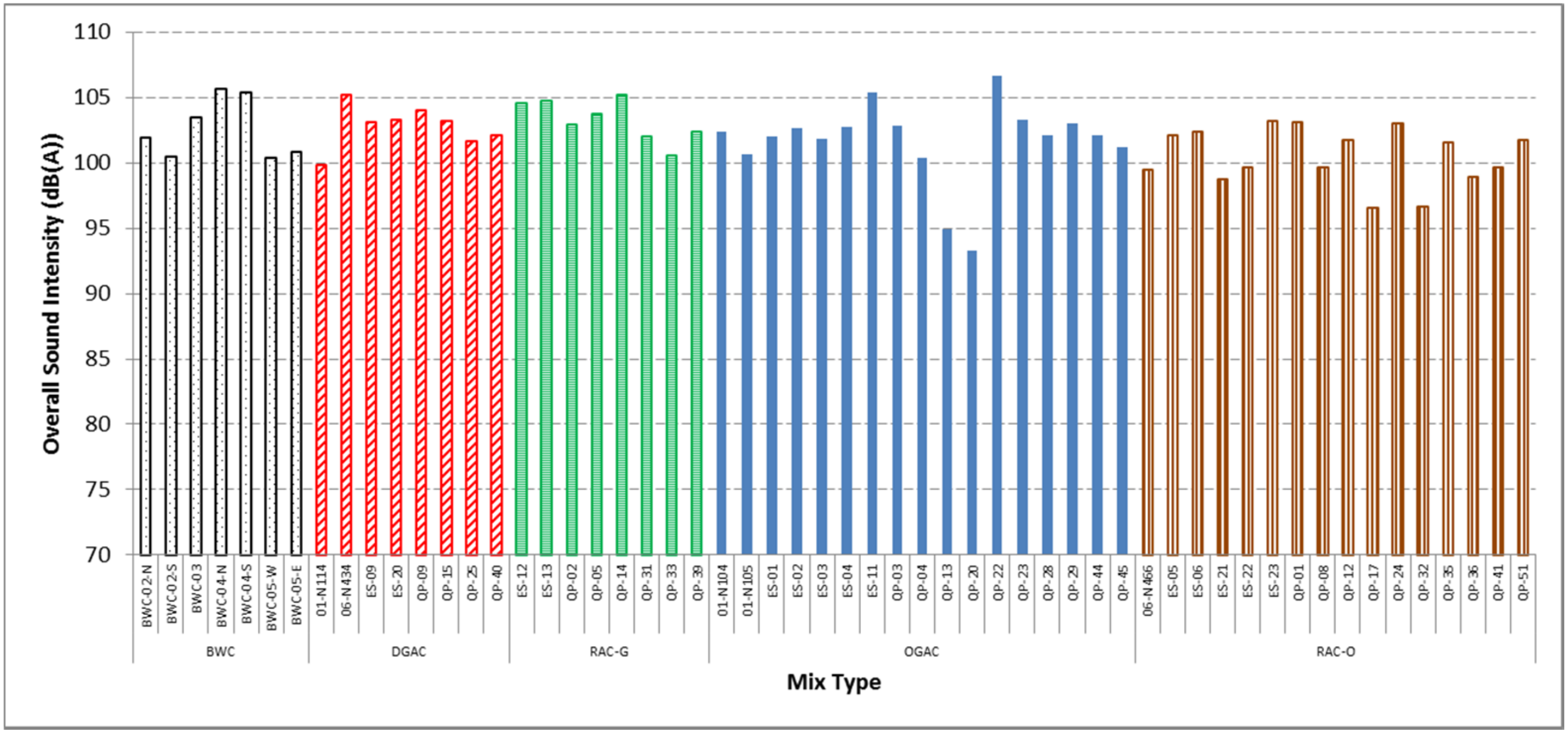


Figure A.41: Sound intensity levels of BWC compared to other pavement types, second round of measurements, 2011.

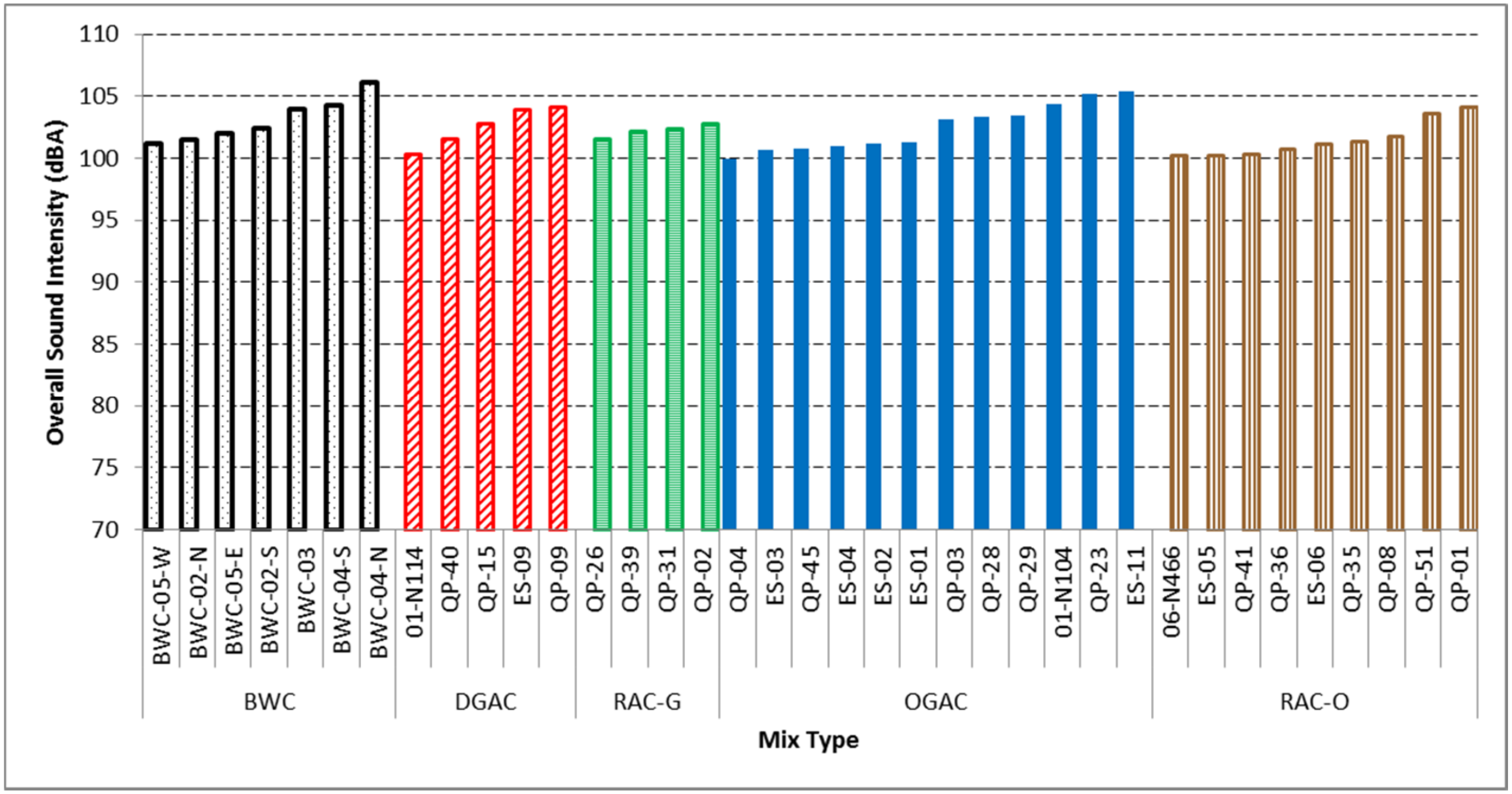
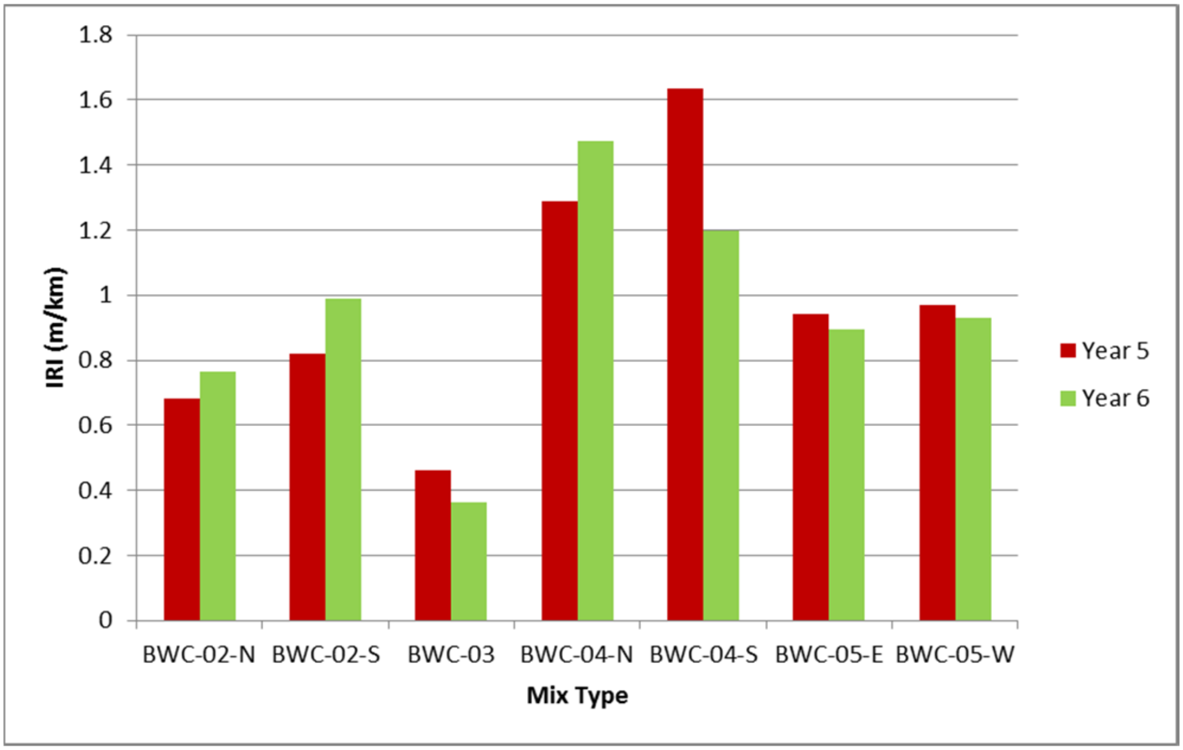
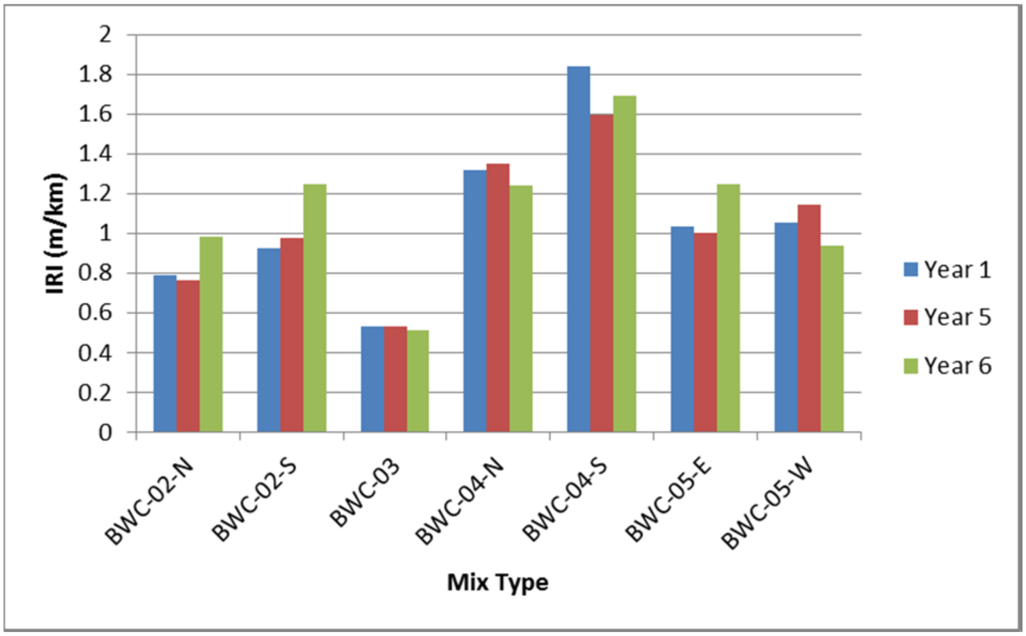


Figure A.42: Sound intensity levels of BWC compared to other pavement types, third round of measurements, 2012.



(a)



(b)

Figure A.43: IRI level for each BWC section: (a) right wheelpath, (b) left wheelpath.

A.5.7 Summary

The following observations were obtained from noise monitoring of the Environmental Sections (ES) on which data were collected in the sixth year of this study:

- From the LA 138 test sections (10 years old in the sixth year of measurement), it was found that the RAC-O mixes had the lowest IRI and OBSI values. The OGAC mix had a low noise level compared to the DGAC mix, but it exhibited a major increase in overall sound intensity in the sixth year. No interaction between noise-reducing properties and thickness was observed.
- After 13 years, the Yolo 80 section still provides good ride quality, according to FHWA guidelines, but it has lost its noise-reducing capabilities. The noise spectra of this section indicate that the increase in noise mainly occurred at frequencies lower than 1,000 Hz, indicating raveling, but the increase also occurred at higher frequencies, indicating loss of air permeability.
- Almost all the BWC sections, which were five to seven years old in the last year of measurement (other than the BWC on LA 138, which was not considered representative of typical design and construction) provided ride quality classified as "good" by the FHWA standards for interstate pavements.
- Polymer-modified open-graded BWC mixes rapidly lost their initial noise-reduction advantage after five to seven years of traffic. The increase in sound intensity of the BWC mixes occurred in both the low and high frequency bands. In the long run, no noise reduction benefit was found for the BWC mix type compared to DGAC.

A.6: References

1. Ongel, A., J. Harvey, E. Kohler, Q. Lu, and B. 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. University of California Pavement Research Center, Berkeley and Davis, California.
2. FHWA (1999). "Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance Report." U.S. Department of Transportation.
3. Lu, Q., E. Kohler, J. Harvey, and A. Ongel (2009). *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results*. UCPRC-RR-2009-01. University of California Pavement Research Center, Berkeley and Davis, California.
4. California Department of Transportation (Caltrans) (2002). "Guide to the Investigation and Remediation of Distress in Flexible Pavements: Office Manual." Caltrans Flexible Pavement Materials Program, Caltrans, Sacramento, California.
5. Bendtsen, H., E. Kohler, and Q. Lu (2009). *Temperature Influence on Road Traffic Noise: A Californian OBSI Measurement Study*. Danish Road Directorate/Road Institute, DRI report.

6. Lu, Q., J. Harvey, and R. Wu (2011). *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Four-Year Results*. UCPRC-RR-2010-05. University of California Pavement Research Center, Berkeley and Davis, California.

APPENDIX B: TEST SECTION LISTS, CALIBRATION OF NOISE RESULTS FOR CONDITIONS AND EQUIPMENT, DATA PLOTS, SPECTRA AND CONDITION SURVEY DATA, AND DETAILS OF REGRESSION PREDICTIONS

Appendix B.1: List of Test Sections Included in the Study

Table B.1: List of Quiet Pavement (QP) Factorial Experiment Sections

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Testing*
Open-graded Asphalt Concrete (OGAC) (conventional and polymer-modified)	Less than 1 year old	High	High	03-PLA-80-1.4/2.6	QP-44	<1	19,250	0
			Low	NA		–	–	
		Low	High	03-YOLl-80-0.0/0.4	QP-45	<1	20,833	0
			Low	05-SCR-152-7.6/8.0	QP-20	<1	3,050	0
	1 to 4 years old	High	High	04-MRN-101-0.0/2.5	QP-28	4	13,625	0
			Low	04-SON-121-3.4/7.3	QP-4	4	8,230	0
		Low	High	04-SCL-237-R3.8/7.10	QP-23	5	15,639	0
			Low	08-SBD-38-S0.0/R5.0	QP-13	5	4,733	0
	5 to 8 years old	High	High	04-MRN-37-12.1/14.4	QP-3	5	8,482	0
			Low	01-MEN-1-0.1/15.2	01-N103 01-N104 01-N105	5	1,450	1 4 4
		Low	High	04-SCL-237-R1.0/2.3	QP-22	8	15,148	0
			Low	03-SAC-16-6.9/20.7	QP-29	8	6,367	0

* *Note:* This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The "0" entry means that the section was tested for OBSI in all six survey years.

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*
Rubberized Open-graded Asphalt Concrete (RAC-O)	Less than 1 year old	High	High	03-PLA-80-14.3/33.3	QP-51	<1	14,167	0
			Low	01-MEN-20-R37.9/43.0	QP-41	<1	5,200	0
				01-LAK-29-R37.3/R37.6	QP-42	<1	5,850	3
		Low	High	06-TUL-99-42.0/47.0	QP-35	<1	10,400	0
			Low	06-TUL-63-19.8/R30.1	QP-34	<1	3,325	0
	1 to 4 years old	High	High	03-SAC-50-16.10/17.30	QP-8	5	17,694	0
			Low	10-AMA-49-14.7/17.6	QP-17	3	4,060	0
		Low	High	07-LA-710-6.8/9.7	QP-1	3	19,208	0
				04-CC-680-23.9/24.9	QP-36	3	17,107	0
			Low	06-TUL-65-21/29	06-N466 06-N467 06-N468	3	4,919	4 2 1
	5 to 8 years old	High	High	No sections found to fit this cell	-	-	-	
			Low	04-NAP-128-5.1/7.4	QP-32	8	1,353	0
		Low	High	04-SCL-85-1.9/4.7	QP-24	8	16,986	0
			Low	08-SBD-58-R0.0/5.3	QP-12	5	6,497	0

* *Note:* This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The “0” entry means that the section was tested for OBSI in all six survey years.

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*
Rubberized Gap-graded Asphalt Concrete (RAC-G)	Less than 1 year old	High	High	No sections found to fit this cell	-	-	-	
			Low	01-MEN-20-R37.9/43.0	QP-39	<1	5,200	0
		Low	High	04-SCl-280-R0.0/R2.7	QP-26	<1	25,667	0
			Low	06-TUL-63-19.8/R30.1	QP-33	<1	4,800	0
	1 to 4 years old	High	High	04-MRN-101-18.9/23.1	QP-2	4	2,100	0
			Low	04-SON-1-0.0/8.4	QP-31	5	2,250	0
		Low	High	08-RIViv-15-33.8/38.4	QP-14	5	19,528	0
			Low	05-SLO-46-R10.8/R22.0	QP-19	4.5	3,233	3
	5 to 8 years old	High	High	04-MRN-101-2.5/8.5	QP-5	9	20,925	0
			Low	10-CAL-4-0/18.8	QP-18	6	2,211	3
		Low	High	11-SD-8-0.8/1.9	QP-46	6	26,607	0
			Low	07-VEN-34-4.3/6.3	QP-10	5	8,007	2

* *Note:* This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The “0” entry means that the section was tested for OBSI in all six survey years.

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*
Dense-graded Asphalt Concrete (DGAC)	Less than 1 year old	High	High	03-PLA-80-14.3/33.3	QP-27	<1	8,333	2
			Low	01-MEN-20-R37.9/43.0	QP-40	<1	5,200	0
		Low	High	06-FRE-99-10.7/15.9	QP-6	<1	15,500	4
			Low	07-LA-138-60.2/61.6	QP-15	<1	7,750	0
	1 to 4 years old	High	High	03-ED-50-17.3/18.3	QP-21	3	12,969	4
			Low	03-ED-50-18.5/20.3	QP-30	4	6,385	0
		Low	High	06-KER-99 29.5/31.0	QP-7	5	10,417	3
			Low	04-SOL-113-0.1/18.0	QP-43	1	2,750	3
	5 to 8 years old	High	High	04-SM-280-9.6/10.8	QP-9	5	10,986	0
			Low	01-MEN-1-20.8/38.7	01-N114	7	813	4
					01-N121	7	581	1
		Low	High	04-ALA-92-6.6/8.8	QP-16	14	6,744	4
			Low	06-KER-65-R0.0/2.9	06-N434	6	3,107	4
					06-N436	6	4,950	1
				07-LA-60 R25.4/R30.5	QP-11	7	29,818	2
				04-CC-680-23.9/24.9	QP-25	8	18,071	2

* *Note:* This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The “0” entry means that the section was tested for OBSI in all six survey years.

Mix Type		Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*
F-mixes	RAC Binder	Less than 1 year old	High	Low	01-MEN-101-37.4/38.8	QP-52	1	4,000	6
		1 to 4 years old	High	Low	01-MEN-101-50.8/ 51.5	QP-47	3	5,081	6
					01-HUM-101-111.1/111.5	QP-50	4	2,130	4
	Conventional Binder	5 to 8 years old	High	Low	01-MEN-20-21.19/21.69	QP-48	8	1,289	6
					01-MEN-20-22.18 /22.68	QP-49	8	1,289	6

* *Note:* This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The “0” entry means that the section was tested for OBSI in all six survey years.

Table B.2: List of Caltrans Environmental Noise Monitoring Site (ES) Sections

Site Name	Site Location	Mix Types, Design Thicknesses, and Site ID*	Construction Date	Survey Year of Dropout for OBSI Test **
Los Angeles 138 (LA 138)	07-LA-138/PM 16.0-21.0	OGAC, 75 mm (ES-1, ES-2) OGAC, 30 mm (ES-3, ES-4) RAC-O, 30 mm (ES-5, ES-6) BWC, 30 mm (ES-7, ES-8) DGAC, 30 mm (ES-9)	Spring 2002	0 0 0 6 0
Los Angeles 19 (LA 19)	07-LA-19/ PM 3.4	European gap-graded, 30 mm (ES-10)	May 2005	6
Yolo 80	03-Yolo-80/PM 2.9-5.8	OGAC, 20 mm (ES-11)	Summer 1998	0
Fresno 33 (Fre 33)	06-Fre-33/PM 70.9-75.08	RAC-G, 45 mm (ES-13) RAC-G, 90 mm (ES-12) RUMAC-GG, 45 mm (ES-14) RUMAC-GG, 90 mm (ES-15) Type G-MB, 45 mm (ES-16) Type G-MB, 90 mm (ES-17) Type D-MB, 45 mm (ES-19) Type D-MB, 90 mm (ES-18) DGAC, 90 mm (ES-20)	Summer 2004	6 6 6 6 6 6 6 6 6
San Mateo 280 (SM 280)	04-SM-280/PM R0.0-R5.6	RAC-O, 45 mm (ES-21)	Fall 2002	6
Sacramento 5 (Sac 5)	03-Sac-5/PM 17.2-17.9 North and southbound directions	RAC-O, 30 mm (ES-22, ES-23)	Summer 2004	6

* *Notes:*
OGAC: Open-graded asphalt concrete
RAC-O: Rubberized open-graded asphalt concrete
BWC: Bonded wearing course
RAC-G: Rubberized gap-graded asphalt concrete (wet process)
RUMAC-GG: Rubber-modified asphalt concrete (dry process, a local-government specification)
Type D-MB: Dense-graded rubberized asphalt concrete (terminal blend)
Type G-MB: Gap-graded rubberized asphalt concrete (terminal blend)
DGAC: Dense-graded asphalt concrete

*******Note:* This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The “0” entry means that the section was tested for OBSI in all six survey years.

Appendix B.2: Development of Calibration Equations for Pavement Temperature, Test Tire, Speed, and Analyzer Equipment *(6)*

B.2.1 Introduction

To investigate the combined effects of speed, pavement temperature, and the use of a particular test tire and/or sound analyzer on On-board Sound Intensity (OBSI) measurements near the tire/pavement interface, two factorial experiments were conducted on several pavement sections around Los Angeles and Davis, California, during May and June of 2010, 2011, and 2012. The test tire and sound analyzer were changed for the reasons discussed in Section 1.3.

This investigation was undertaken after an unexpectedly large increase in sound intensity measured in the fourth year of testing of the Quieter Pavement (QP) and Environmental Sections (ES) sections was discovered after data calibration. Because a different SRTT (SRTT#2) was used in the fourth year than in the third year (SRTT#1), it was suspected that significant differences exist among the various SRTT tires. Several additional experiments were then conducted in late 2010 and early 2011 to develop calibration equations for the different SRTT tires that had been used in the UCPRC noise studies. Four tires (SRTT#A, SRTT#B, SRTT#3, and SRTT#4) had been included in these experiments, which were conducted on both asphalt and concrete pavements. The tires named SRTT#A and SRTT#B in Year 2 of data collection were renamed SRTT#1 and SRTT#2, respectively. In these additional experiments, calibration between analyzers (Larson Davis and Harmonie) was also further investigated using different tires on both AC and PCC pavements.

The first experiment was conducted on seven pavement sections (ODR-N, ODR-S, RD105-N, RD105-S, RD32a-E, RD32a-W1, and RD32a-W2) near Davis during late May through early June 2010. On each section, OBSI was measured with three repetitions at all factor-level combinations of four variables: test tire (Aquatred 3 #3, SRTT#3), speed (35 mph, 60 mph), sound analyzer (Larson Davis, Harmonie), and pavement temperature (low [early morning], high [noon]). During this first set of tests, pavement temperatures ranged between 18°C and 44°C.

The second experiment was conducted on seven experimental test sections on LA 138 (State Route 138) in Los Angeles County (see Table B.2) during mid-June 2010. On each section, OBSI was measured with three repetitions at all factor-level combinations of three variables: test tire (Aquatred 3 #3, SRTT#3), speed (35 mph, 60 mph), and pavement temperature (low [early morning], high [noon]). When these measurements were taken, Pavement temperatures ranged between 13°C and 52°C. In this experiment only the Harmonie sound analyzer was used. The same sets of experiments were repeated using SRTT#4 and SRTT#5 in June 2011 and 2012 at the same locations.

Results from these factorial experiments were analyzed after each year and then applied to the sound intensity data in order to convert that data to a reference condition.

Table B.3 summarizes the experiments undertaken to develop calibration equations. In this table, the first two experiment numbers, 1 and 2, are the two factorial experiments discussed above. Experiments 3 through 7 were added for calibrating the various SRTT tires, and experiments 8 through 11 were added for calibration between the Larson Davis and Harmonie analyzers.

Table B.3: Summary of Experiments for Development of Calibration Equations

No.	Plan ID	Year	Section Set	Plan Description	Notes
1	Calibration_2010_ Davis	2010	Davis Calibration Sections (AC and PCC)	Full factorial on tire type, speed, pavement temperature, and analyzer	Used SRTT#3 and Aquatred 3 #3
2	Calibration_2010_ LA138	2010	LA 138 Sections (AC)	Same as Calibration_2010_Davis except no analyzer effect	Used SRTT#3 and Aquatred 3 #3
3	Tire_2010_Davis	2010	Davis Calibration Sections (AC and PCC)	Develop correlation between SRTT#1, #2, #3, and #4	It is believed that SRTT#A = SRTT#1 and SRTT#B = SRTT#2 based on the fact that SRTT#B is noisier and harder than #A.
4	Tire_2010_Local_ PCC	2010	Davis Nearby PCC Sections	Same as Tire_2010_Davis except on PCC sections	Using SRTT#A, #B, #3, and #4
5	Tire_2010_LA138	2010	LA 138 Sections (AC)	Same as Tire_2010_Davis except on different sections	Using SRTT#A, #B, #3, and #4
6	Tire_2012_Davis	2012	Davis Calibration Sections (AC and PCC)	Develop correlation between SRTT#1and #5	Using SRTT#1 and #5
7	Tire_2012_LA138	2012	LA 138 Sections (AC)	Develop correlation between SRTT#1and #5	Using SRTT#1 and #5
8	Analyzer_2010_ LA138	2010	LA 138 Sections (AC)	Use both Harmonie and Larson Davis to test LA 138 again to establish analyzer correction	Using SRTT#3
9	Analyzer_2010_ Firebaugh	2010	Firebaugh Sections (AC)	Use both Harmonie and Larson Davis to test Firebaugh sections again to establish analyzer correction	Using SRTT#4
10	Calibration_2010_ Davis_Extra	2010	Davis RD32a Sections (PCC)	Extra runs not included in Calibration_2010_Davis because pavement temperature was not the lowest; use both Harmonie and Larson Davis.	Marked as low temp but really wasn't the lowest one. Using Aquatred 3 #3.
11	Analyzer_2011_ Local_PCC	2011	Davis nearby PCC Sections	Use both Harmonie and Larson Davis to test nearby PCC sections	Using SRTT#3

B.2.2 Analysis and Modeling of the Two Factorial Experiment Results

Since the second experiment only included one sound analyzer (Harmonie), combining the measurements from both experiments created an unbalanced data set, which posed severe problems in estimating the effect of sound analyzer equipment. Therefore, an analysis of variance (ANOVA) was first conducted on the data from the first experiment to identify significant factors among all the main effects and second-order interaction terms. Once the significant factors (at the 95 percent confidence level in this study) were determined, a linear regression analysis was performed to estimate the parameter corresponding to each significant factor. The estimation results are shown in Table B.4. As can be seen, the interactions between equipment and other variables (speed, tire, and pavement temperature) are generally insignificant for OBSI at all the one-third octave frequency bands except for the 4,000 Hz and 5,000 Hz bands, where the effect of equipment type interacts with the effect of speed level (35 mph or 60 mph).

Excluding the data measured with the Larson Davis sound analyzer balances the pooled data from both experiments (i.e., same number of observations at all factor level combinations). An ANOVA on this data set further identified significant factors on a wider range of pavement sections. The identified significant variables and corresponding estimated parameters from linear regression analyses are shown in Table B.8. The estimated parameters (coefficients) in Table B.4 through Table B.8 can be used to calibrate OBSI measurements to equivalent values under certain reference conditions. However, calibration based on these models assumes a constant difference between two levels of one factor. For example, for 400 Hz OBSI, Table B.4 shows that the Harmonie analyzer always gives a value -2.240157 dBA lower than the value measured with Larson Davis analyzer, no matter how large the 400 Hz OBSI is. This assumption is not necessary true though, and may therefore introduce large errors in the calibrated data.

Another approach was then suggested for calibrating the OBSI data: based on the statistical significance identified in the ANOVA for each main effect and interaction term, a simple linear regression was performed on paired observations for each significant factor. In this approach, the calibration was conducted sequentially based on the simple linear regression results. Specifically, the original OBSI data were calibrated to a reference condition (e.g., SRTT#1, Larson Davis equipment, 60 mph, and 25°C pavement temperature) following the steps below:

1. Calibrate for air density following the procedure in Reference *(1)* of Appendix A.
2. Calibrate for type of test tire (Aquatred 3#2 versus SRTT#1) using the equations in Reference *(3)* of Appendix A.
3. Calibrate for type of sound analyzer equipment using the parameters in Table B.12. Figure B.1 shows a comparison of overall OBSI values measured with the Larson Davis Analyzer and the Harmonie

Analyzer on AC and PCC pavements. It can be seen that the correlation is not significantly affected by pavement surface type. Therefore, the data from both pavement types were combined to estimate the calibration parameters presented in Table B.12.

4. Calibrate for test vehicle speed using the parameters in Table B.13 and Table B.14.
5. Calibrate for pavement temperature using the parameters in Table B.15.

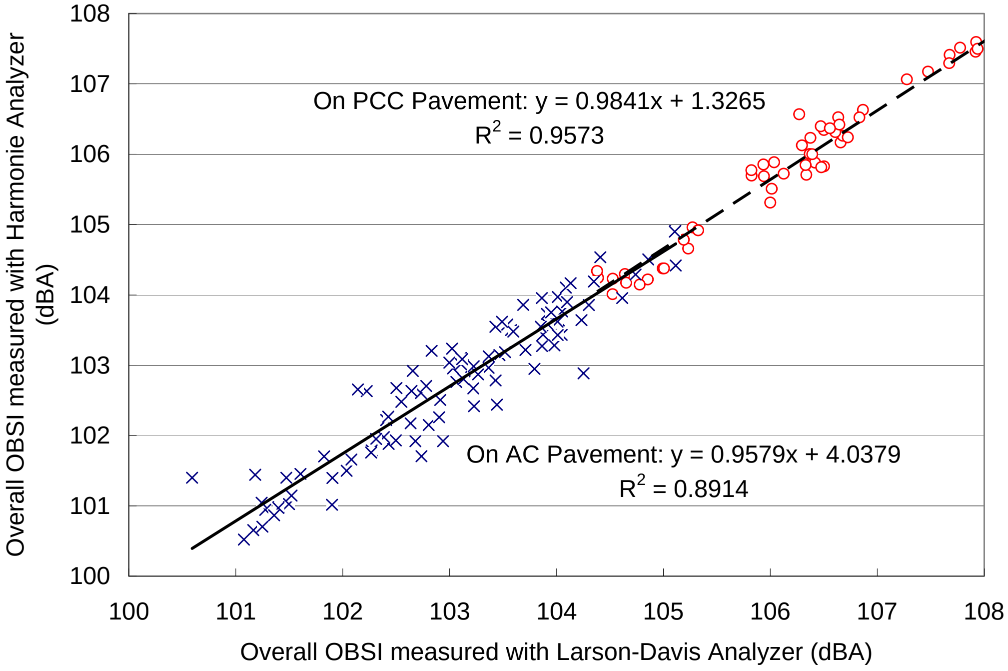


Figure B.1: Comparison of overall OBSI values measured with the Larson Davis analyzer and the Harmonie analyzer on AC and PCC Pavements.

Table B.4: Regression Estimation Results for 400 Hz – 800 Hz OBSI Data Based on Davis Experiment

Variable	400 Hz		500 Hz		630 Hz		800 Hz	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Intercept	87.267489	<2e-16	90.8568	<2e-16	94.69849	<2e-16	100.7043	<2e-16
Equipment_Harmonie	-2.240157	<2e-16	-1.76316	6.01E-11	-1.97258	4.71E-14	-0.89028	1.81E-05
Tire_Aquatred	3.441456	1.52E-05	2.49052	6.52E-11	2.09021	0.0187	0.85159	4.26E-05
Speed_35mph	-5.819413	<2e-16	-6.06326	<2e-16	-6.61749	<2e-16	-7.59271	<2e-16
Temperature	-0.003208	0.8479	-0.03714	0.0125	-0.02147	0.2551	-0.02945	0.0115
Equipment_Harmonie*Tire_Aquatred								
Equipment_Harmonie*Speed_35mph								
Equipment_Harmonie*Temperature								
Tire_Aquatred*Speed_35mph			1.18606	0.0237				
Tire_Aquatred*Temperature	-0.053363	0.0354			-0.05303	0.0635		
Speed_35mph*Temperature								
Residual Standard Error	2.129 on 366 DF		2.505 on 366 DF		2.4 on 366 DF		1.963 on 367 DF	
R-square	0.7042		0.6338		0.6808		0.7961	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is

$$\text{400 Hz OBSI } (\text{dBA}) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.5: Regression Estimation Results for 1,000 Hz – 2,000 Hz OBSI Data Based on Davis Experiment

Variable	**1,000 Hz**		**1,250 Hz**		**1,600 Hz**		**2,000 Hz**	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Intercept	98.306697	<2e-16	97.49826	<2e-16	97.00729	< 2E-16	94.306573	<2e-16
Equipment_Harmonie	-1.368448	<2e-16	-1.71652	<2e-16	-1.662404	< 2E-16	-1.727353	<2e-16
Tire_Aquatred	3.172145	1.23E-11	1.07264	5.48E-10	1.43064	< 2E-16	0.699508	<2e-16
Speed_35mph	-8.096755	<2e-16	-8.9182	<2e-16	-9.150354	< 2E-16	-9.073492	<2e-16
Temperature	0.002638	0.7847	-0.02116	0.00181	-0.039613	< 2E-16	-0.042667	<2e-16
Equipment_Harmonie*Tire_Aquatred								
Equipment_Harmonie*Speed_35mph								
Equipment_Harmonie*Temperature								
Tire_Aquatred*Speed_35mph			0.63043	0.00825				
Tire_Aquatred*Temperature	-0.029658	0.0428						
Speed_35mph*Temperature								
Residual Standard Error	1.229 on 366 DF		1.139 on 366 DF		0.7367 on 367 DF		0.7042 on 367 DF	
R-square	0.9244		0.939		0.9765		0.9778	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is :

$$\text{400 Hz OBSI } (\text{dBA}) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.6: Regression Estimation Results for 2,500 Hz – 5,000 Hz OBSI Data Based on Davis Experiment

Variable	**2,500 Hz**		**3,150 Hz**		**4,000 Hz**		**5,000 Hz**	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Intercept	90.790525	<2e-16	85.83699	<2e-16	82.466918	<2e-16	80.43229	<2e-16
Equipment_Harmonie	-1.737763	<2e-16	-1.675705	<2e-16	-2.103915	<2e-16	-3.086838	<2e-16
Tire_Aquatred	0.021032	0.788	1.330337	<2e-16	1.95939	<2e-16	1.441034	<2e-16
Speed_35mph	-8.953544	<2e-16	-8.666086	<2e-16	-9.295093	<2e-16	-9.858498	<2e-16
Temperature	-0.043341	<2e-16	-0.046889	5.80E-15	-0.044409	1.01E-12	-0.055617	<2e-16
Equipment_Harmonie*Tire_Aquatred								
Equipment_Harmonie*Speed_35mph					0.339816	0.024158	0.564247	0.000736
Equipment_Harmonie*Temperature								
Tire_Aquatred*Speed_35mph			0.431137	0.00305	0.591399	0.000103	0.723893	1.79E-05
Tire_Aquatred*Temperature								
Speed_35mph*Temperature			-0.020828	0.0106	-0.016768	0.049223		
Residual Standard Error	0.745 on 367 DF		0.6906 on 365 DF		0.7191 on 364 DF		0.7991 on 365 DF	
R-square	0.9744		0.9792		0.9794		0.9746	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI } (\text{dBA}) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.7: Regression Estimation Results for Overall OBSI Based on Davis Experiment

Variable	**Overall** **Coefficient**	 **P-value**
Intercept	105.983549	<2e-16
Equipment_Harmonie	-1.414839	<2e-16
Tire_Aquatred	1.391065	<2e-16
Speed_35mph	-7.926374	<2e-16
Temperature	-0.027389	0.00138
Equipment_Harmonie*Tire_Aquatred		
Equipment_Harmonie*Speed_35mph		
Equipment_Harmonie*Temperature		
Tire_Aquatred*Speed_35mph		
Tire_Aquatred*Temperature		
Speed_35mph*Temperature		
Residual Standard Error	1.438 on 367	
R-square	0.8914	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }\left(\text{dBA}\right) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;

if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;

if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.

Temperature is a continuous variable with a unit of degree-Celsius.

Table B.8: Regression Estimation Results for 400 Hz – 800 Hz OBSI Data Measured with Harmonie Analyzer

Parameter	400 Hz		500 Hz		630 Hz		800 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	85.00795	<2e-16	87.67398	<2e-16	91.88879	<2e-16	97.55541	<2e-16
Tire_Aquatred	0.999419	0.000778	2.342435	7.56E-13	0.467116	0.0341	0.761535	0.000614
Speed_35mph	-6.02908	<2e-16	-5.30661	<2e-16	-5.74776	<2e-16	-7.00157	<2e-16
Temperature	-0.03758	1.68E-06	-0.04989	3.81E-09	-0.05635	1.78E-11	-0.01837	0.02509
Tire_Aquatred*Speed_35mph	1.155647	0.005887	1.424581	0.00155				
Tire_Aquatred*Temperature								
Speed_35mph*Temperature								
Residual Standard Error	2.09 on 397 DF		2.238 on 397 DF		2.201 on 398 DF		2.209 on 398 DF	
R-square	0.6586		0.6214		0.6497		0.7207	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }\left(\text{dBA}\right) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$
$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.9: Regression Estimation Results for 1,000 Hz – 2,000 Hz OBSI Data Measured with Harmonie Analyzer

Parameter	1,000 Hz		1,250 Hz		1,600 Hz		2,000 Hz	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Intercept	96.10816	<2e-16	94.85625	<2e-16	93.8864	<2e-16	91.0258	<2e-16
Tire_Aquatred	2.11134	<2e-16	1.145633	1.38E-09	1.765192	<2e-16	0.869567	7.92E-08
Speed_35mph	-7.51168	<2e-16	-8.25975	<2e-16	-8.42221	<2e-16	-8.48323	<2e-16
Temperature	-0.02141	0.000923	-0.03106	3.83E-10	-0.05345	<2e-16	-0.04327	1.14E-12
Tire_Aquatred*Speed_35mph			0.607719	0.0204				
Tire_Aquatred*Temperature								
Speed_35mph*Temperature								
Residual Standard Error	1.734 on 398 DF		1.31 on 397 DF		1.66 on 398 DF		1.59 on 398 DF	
R-square	0.8372		0.907		0.8753		0.8807	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }\left(\text{dBA}\right) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$
$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.10: Regression Estimation Results for 2,500 Hz – 5,000 Hz OBSI Data Measured with Harmonie Analyzer

Parameter	2,500 Hz		3,150 Hz		4,000 Hz		5,000 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	87.79607	<2e-16	83.47042	<2e-16	79.40459	<2e-16	76.78138	<2e-16
Tire_Aquatred	0.458477	0.000222	1.568983	<2e-16	2.788376	<2e-16	1.594221	<2e-16
Speed_35mph	-8.59103	<2e-16	-8.6599	<2e-16	-11.2491	<2e-16	-9.20009	<2e-16
Temperature	-0.04172	<2e-16	-0.04798	<2e-16	-0.03468	2.41E-06	-0.06215	<2e-16
Tire_Aquatred*Speed_35mph			0.540814	0.00316	0.767649	0.000711	0.69554	0.0032
Tire_Aquatred*Temperature					-0.02329	0.005445		
Speed_35mph*Temperature			-0.0156	0.02122	0.059899	3.31E-12		
Residual Standard Error	1.232 on 398 DF		0.912 on 396 DF		1.127 on 395 DF		1.174 on 397 DF	
R-square	0.9261		0.9625		0.947		0.9396	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }(\text{dBA}) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$

$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;

if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;

if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.

Temperature is a continuous variable with a unit of degree-Celsius.

Table B.11: Regression Estimation Results for Overall OBSI Measured with Harmonie Analyzer

Parameter	Overall	
	Coefficient	P-value
Intercept	102.9963	<2e-16
Tire_Aquatred	1.381321	2.35E-14
Speed_35mph	-7.29377	<2e-16
Temperature	-0.03091	2.39E-06
Tire_Aquatred*Speed_35mph		
Tire_Aquatred*Temperature		
Speed_35mph*Temperature		
Residual Standard Error	1.746 on 398 DF	
R-square	0.8221	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI } \left(\text{dBA}\right) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$
$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson Davis equipment is used, “Equipment_Harmonie”=0;

if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT#3 tire is used, “Tire_Aquatred”=0;

if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.

Temperature is a continuous variable with a unit of degree-Celsius.

Table B.12: Calibration Parameters for Sound Analyzer Equipment

One-Third Octave Band	Speed (mph)	Slope*	Intercept	R^2
400	-	0.9765	4.1048	0.964
500	-	0.9978	1.8798	0.987
630	-	1.0257	-0.4471	0.988
800	-	1.0213	-1.2074	0.989
1,000	-	1.0235	-0.8917	0.992
1,250	-	1.0112	0.6458	0.993
1,600	-	1.0148	0.2472	0.993
2,000	-	1.0212	-0.2081	0.993
2,500	-	1.0116	0.6869	0.994
3,150	-	1.0163	0.2721	0.992
4,000	35	0.9176	7.4976	0.929
4,000	60	0.8552	13.624	0.913
5,000	35	0.9237	7.5707	0.908
5,000	60	0.8294	16.035	0.860
Overall	-	1.0178	-0.427	0.994

**Note:* The calibration equation is (OBSI with Larson Davis) = (OBSI with Harmonie)*Slope + Intercept.

Table B.13: Speed Calibration Parameters for SRTT#3

One-Third Octave Band	Slope*	Intercept	R^2
400	1.0099	5.2385	0.666
500	1.3718	-24.806	0.864
630	1.3400	-23.451	0.889
800	1.2410	-15.036	0.838
1,000	1.2892	-17.766	0.946
1,250	1.2831	-15.955	0.900
1,600	1.2545	-12.98	0.926
2,000	1.1516	-3.7188	0.945
2,500	1.0141	7.7036	0.919
3,150	0.9146	15.498	0.884
4,000	0.7622	26.134	0.587
5,000	1.0054	9.056	0.918
Overall	1.3058	-21.718	0.943

**Note:* The calibration equation is (OBSI at 60 mph) = (OBSI at 35 mph)*Slope + Intercept.

Table B.14: Speed Calibration Parameters for Aquatred 3 #3 Tire

One-Third Octave Band	Slope*	Intercept	R^2
400	1.309	-20.005	0.832
500	1.6516	-51.565	0.855
630	1.3977	-27.653	0.914
800	1.1847	-9.3743	0.884
1,000	1.2825	-18.04	0.948
1,250	1.3663	-24.397	0.918
1,600	1.2428	-12.199	0.932
2,000	1.2647	-13.257	0.926
2,500	1.1197	-0.8175	0.893
3,150	0.9275	14.195	0.871
4,000	0.8633	18.752	0.679
5,000	1.0329	6.4302	0.930
Overall	1.313	-22.801	0.961

**Note:* The calibration equation is (OBSI at 60 mph) = (OBSI at 35 mph)*Slope+Intercept.

Table B.15: Pavement Temperature Calibration Parameters

	SRTT#3, 60 mph	Aquatred 3 #3, 60 mph	SRTT#3 or Aquatred 3 #3, 35 mph
One-Third Octave Band	Slope	Slope	Slope
400	-0.03758	-0.03758	-0.03758
500	-0.04989	-0.04989	-0.04989
630	-0.05635	-0.05635	-0.05635
800	-0.01837	-0.01837	-0.01837
1,000	-0.02141	-0.02141	-0.02141
1,250	-0.03106	-0.03106	-0.03106
1,600	-0.05345	-0.05345	-0.05345
2,000	-0.04327	-0.04327	-0.04327
2,500	-0.04172	-0.04172	-0.04172
3,150	-0.04798	-0.04798	-0.06358
4,000	-0.03468	-0.05797	0.001929
5,000	-0.06215	-0.06215	-0.06215
Overall	-0.03091	-0.03091	-0.03091

**Note:* The calibration equation is (OBSI at 25ºC) = (OBSI at other temperature in Celsius) + (25 minus other temperature in Celsius)*Slope.

B.2.3 Analysis and Modeling of the Additional Experiment Results

Experiments 3 through 7 in Table B.3 were conducted to investigate the relationship between the five SRTT tires (SRTT#A [#1], SRTT#B [#2], SRTT#3, SRTT#4, and SRTT#5). SRTT#1 was used in the second and third years of measurement of OBSI on AC pavements, while SRTT#2 was used in the fourth year data collection, SRTT#3 and SRTT#4 were used in the fifth year data collection on AC pavements, and SRTT#5 was used in the sixth year of data collection. SRTT#2, SRTT#3, SRTT#4, and SRTT#5 were also used to collect the OBSI data in the first, second, third, and fourth years of testing on PCC pavements, respectively. Experiments 3 through 7 included both AC and PCC sections, and used only the Harmonie analyzer to process noise data. Figure B.2 and Figure B.3 show comparisons of overall OBSI values measured with different SRTT tires on AC pavement and PCC pavement, respectively. It can be seen that the values measured with SRTT#2 are significantly different from the values measured with the other SRTT tires.

Simple linear regression analysis was conducted for various pairs of SRTT tires, for AC sections only, and for PCC sections only. The results are summarized in Table B.16 and Table B.17, respectively.

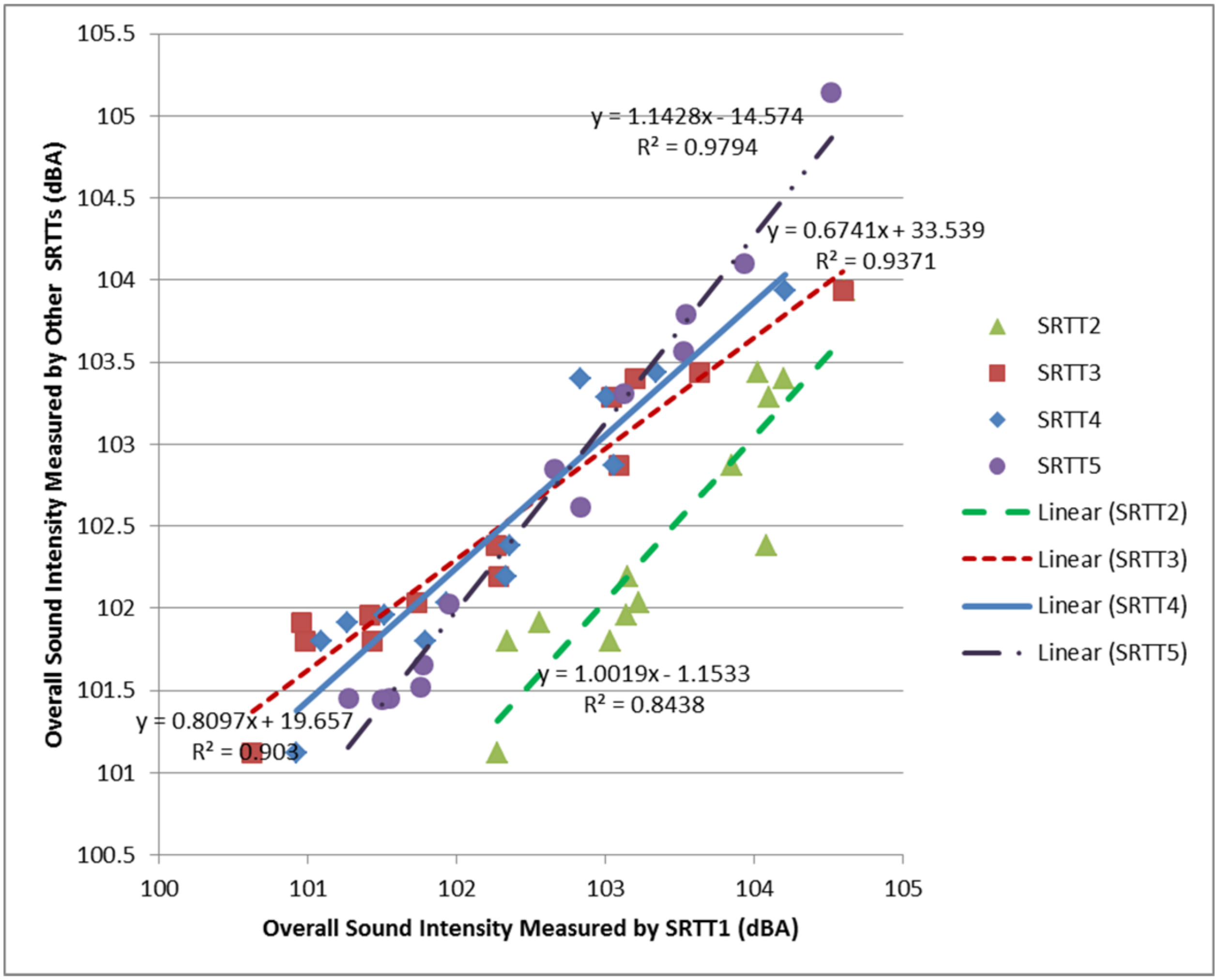


Figure B.2: Comparison of overall OBSI measured with various SRTT tires on AC pavements.

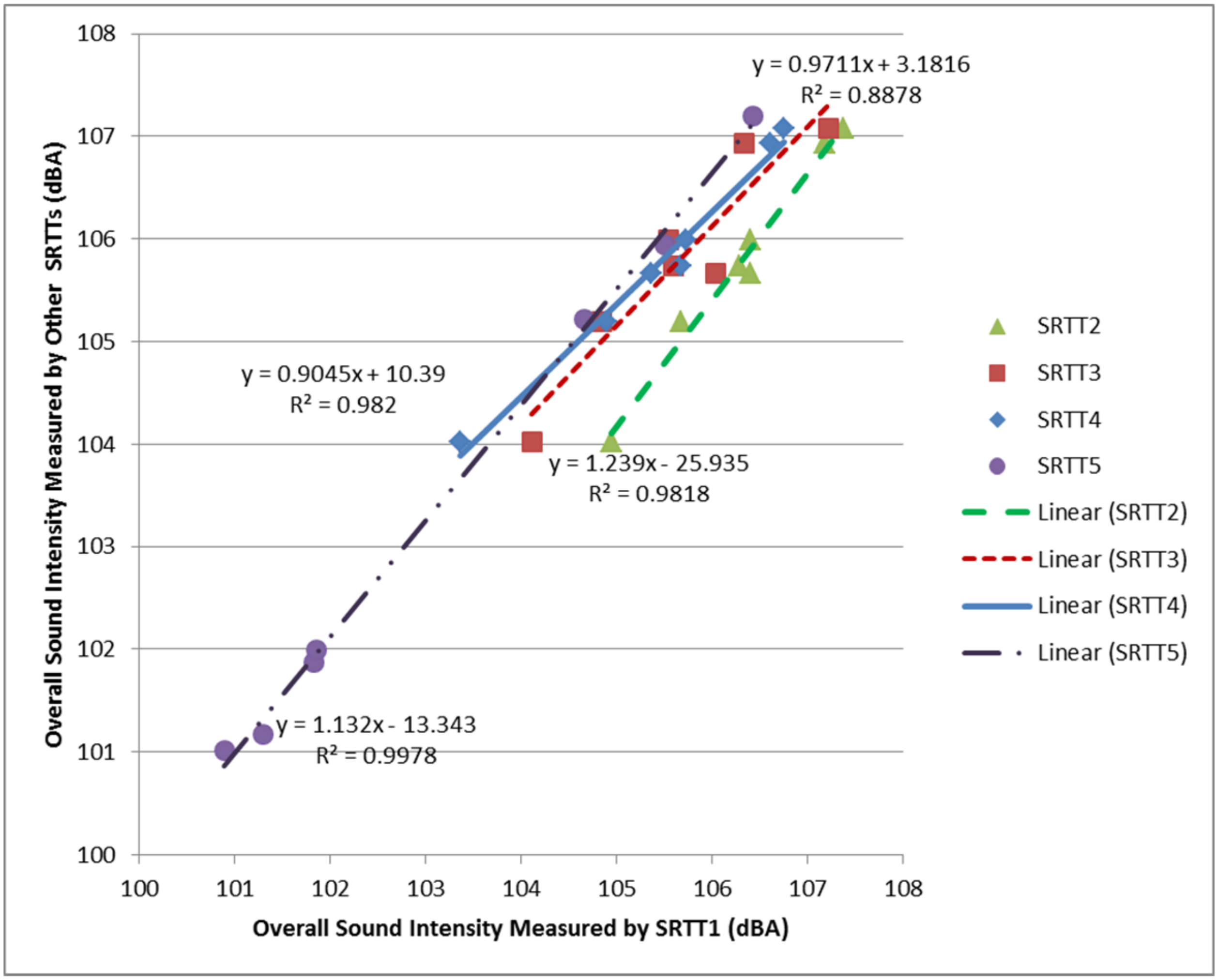


Figure B.3: Comparison of overall OBSI measured with various SRTT tires on PCC pavements.

Table B.16: SRTT Tire Calibration Parameters on AC Pavements

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

Table B.17: SRTT Tire Calibration Parameters on PCC Pavements

	SRTT#2 to SRTT#1			**SRTT#3 to SRTT#1**		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	0.772	1.004	0.73	23.847	0.735	0.81
500	-3.033	1.032	0.95	-10.202	1.117	0.85
630	1.374	0.987	0.98	-2.912	1.035	0.92
800	-5.173	1.050	0.99	-9.376	1.095	0.96
1,000	5.223	0.938	0.68	3.293	0.966	0.99
1,250	-1.000	1.002	0.97	4.195	0.958	0.94
1,600	-5.256	1.048	0.98	14.262	0.851	0.95
2,000	-6.638	1.060	0.96	8.604	0.909	0.95
2,500	1.452	0.974	0.97	7.992	0.909	0.96
3,150	-1.296	1.009	0.97	16.262	0.807	0.94
4,000	-0.307	1.001	0.97	14.062	0.830	0.93
5,000	0.387	0.996	0.97	10.427	0.868	0.92
Overall	-25.935	1.239	0.98	3.182	0.971	0.89
	SRTT#4 to SRTT#1			**SRTT#5 to SRTT#1**		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	0.165	0.999	0.96	-1.954	1.020	0.95
500	-5.181	1.059	0.95	-8.873	1.108	0.98
630	1.911	0.979	0.97	-5.693	1.076	0.99
800	2.978	0.971	0.98	-13.890	1.146	1.00
1,000	18.903	0.811	0.96	-5.125	1.049	0.98
1,250	1.902	0.987	0.96	7.733	0.922	0.96
1,600	14.482	0.856	0.99	5.571	0.950	0.99
2,000	7.213	0.933	1.00	-17.911	1.205	0.99
2,500	4.920	0.950	0.99	-103.542	2.187	0.91
3,150	6.546	0.926	0.99	-64.698	1.791	0.80
4,000	6.093	0.930	0.99	50.546	0.361	0.06
5,000	7.561	0.908	0.98	0.650	0.999	0.24
Overall	10.390	0.905	0.98	-13.343	1.132	1.00

Experiments 6 through 9 in Table B.3 were conducted to investigate the relationship between the Larson Davis and Harmonie analyzers. Both AC and PCC pavements and several tires were included in the experiments. It is believed that the calibration between analyzer equipment types is independent of pavement type and tire type, which is partially verified by the results of factorial experiments 1 and 2 in Table B.3. Simple linear regression analysis was conducted on the data from the four experiments. The results are summarized in Table B.18.

Table B.18: Sound Analyzer Equipment Calibration Parameters on AC and PCC Pavements

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

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

B.2.4 Calibration of OBSI Data for This Report

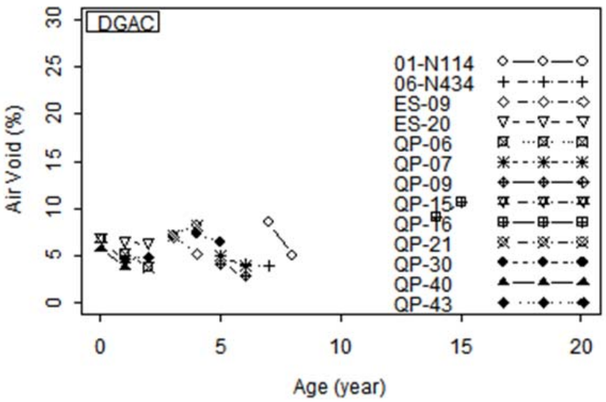
After reviewing the first five-year data analysis and the calibration equations developed in this section, Caltrans and UCPRC reached an agreement regarding how to handle the calibration of OBSI data for the six-year analysis report. It was agreed that UCPRC would take the following steps in preparing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

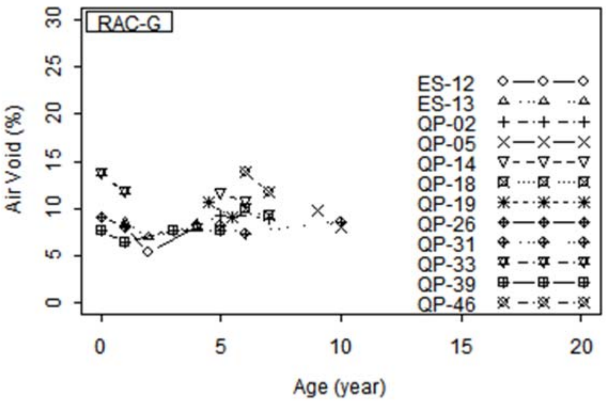
1. Disregard calibration for pavement temperature.
2. Remove all OBSI data measured at a test car speed other than 60 mph.
3. Calibrate the first three years of AC data from the Larson Davis to the Harmonie equipment using the parameters in Table B.18.
4. Calibrate the sixth year data from SRTT#5 to SRTT#1 using parameters in Table B.16.
5. Calibrate the fifth year data from SRTT#4 to SRTT#1 using parameters in Table B.16.
6. Calibrate the fourth year data from SRTT#2 to SRTT#1 using parameters in Table B.16.
7. Calibrate the first two years of AC data from Aquatred 3 #2 tire to SRTT#1 using equations developed in Reference *(3)* of Appendix A.
8. Calibrate all data for air density following the procedure in Reference *(1)* of Appendix A.

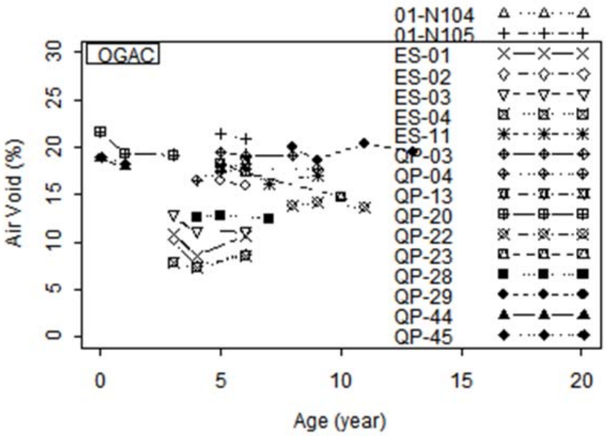
The reference conditions for OBSI data in this report are 60 mph test car speed, SRTT#1 tire, and Harmonie analyzer.

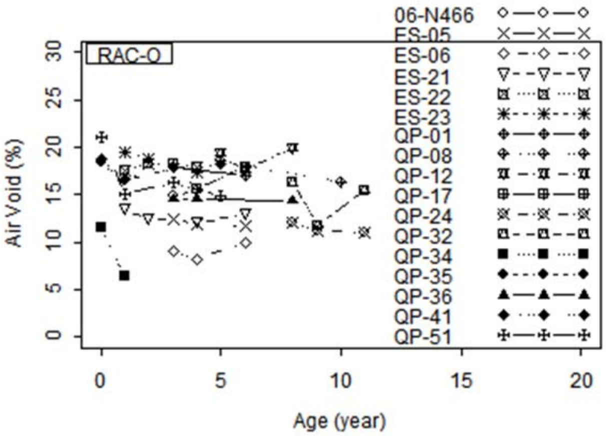
Appendix B.3: Plots of Air-Void Content and Permeability

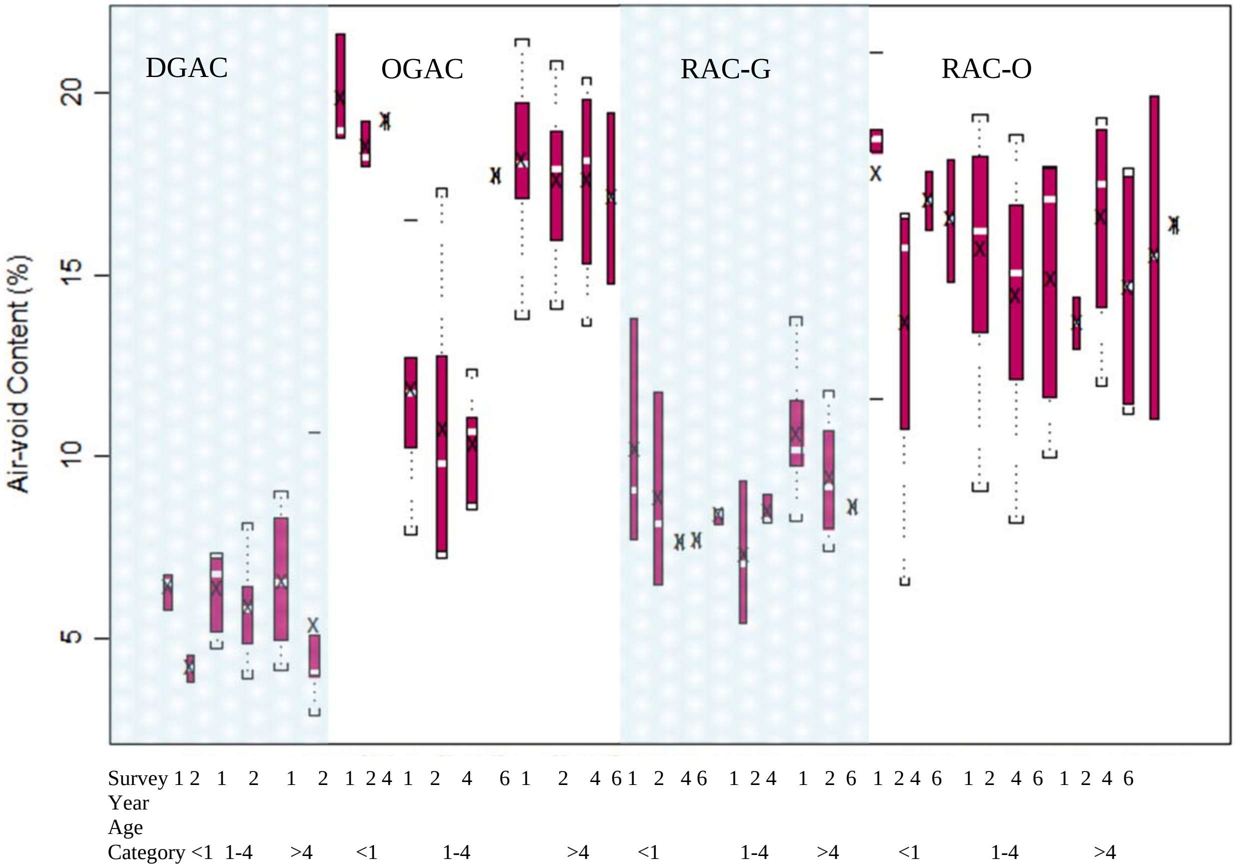
B.3.1 Trend Lines and Box Plots of Air-Void Content



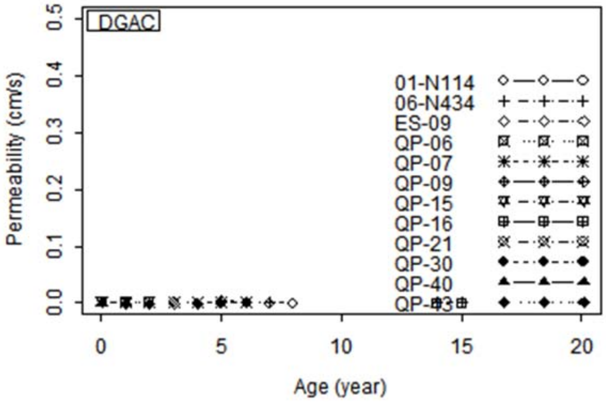


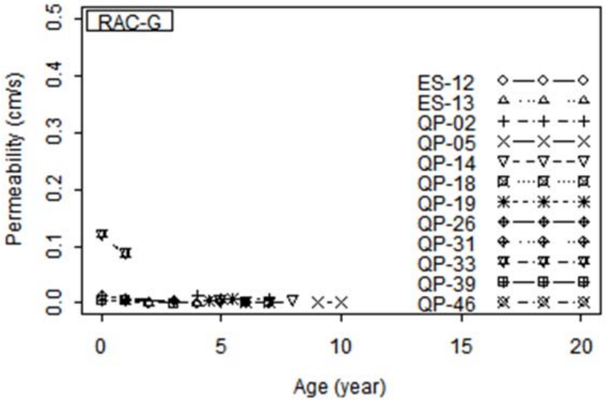


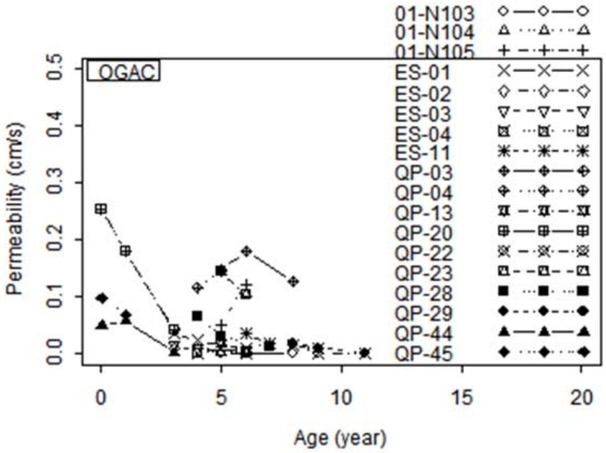


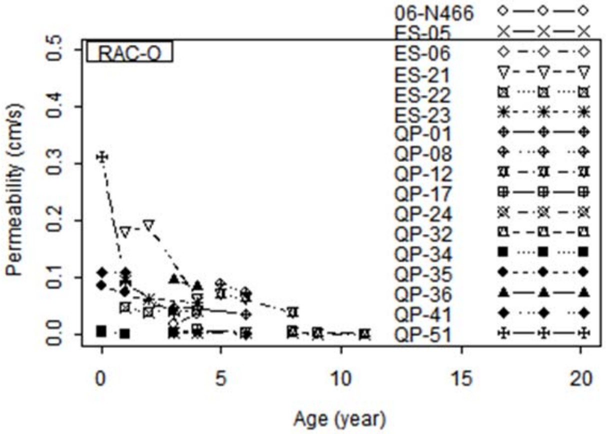

DGAC
OGAC
RAC-G
RAC-O
Air-void Content (%)
20
15
10
5
Survey 1 2 1 2 1 2 1 2 4 1 2 4 6 1 2 4 6 1 2 4 6 1 2 4 1 2 6 1 2 4 6 1 2 4 6 1 2 4 6
Year
Age
Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

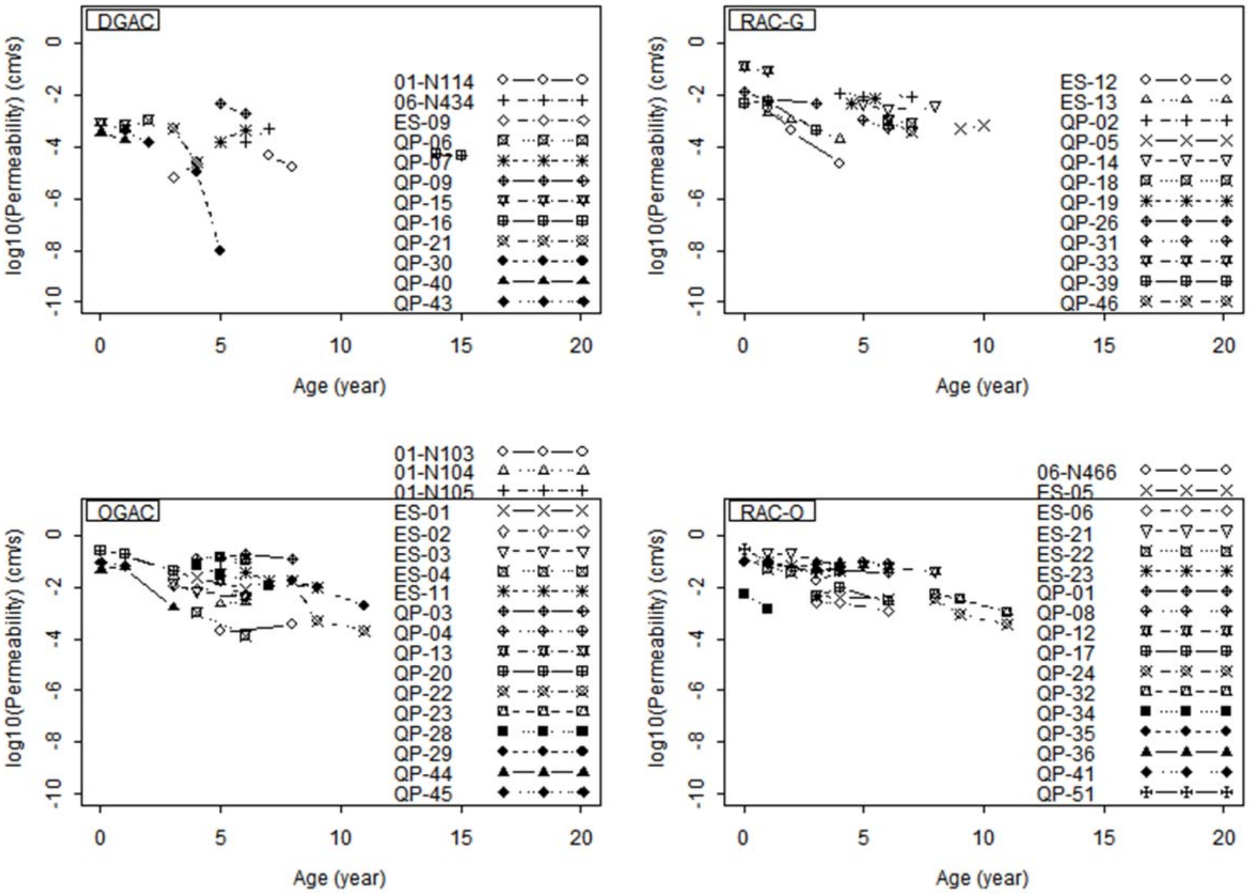
B.3.2 Trend Lines, Box Plots, and Regression Analysis of Permeability

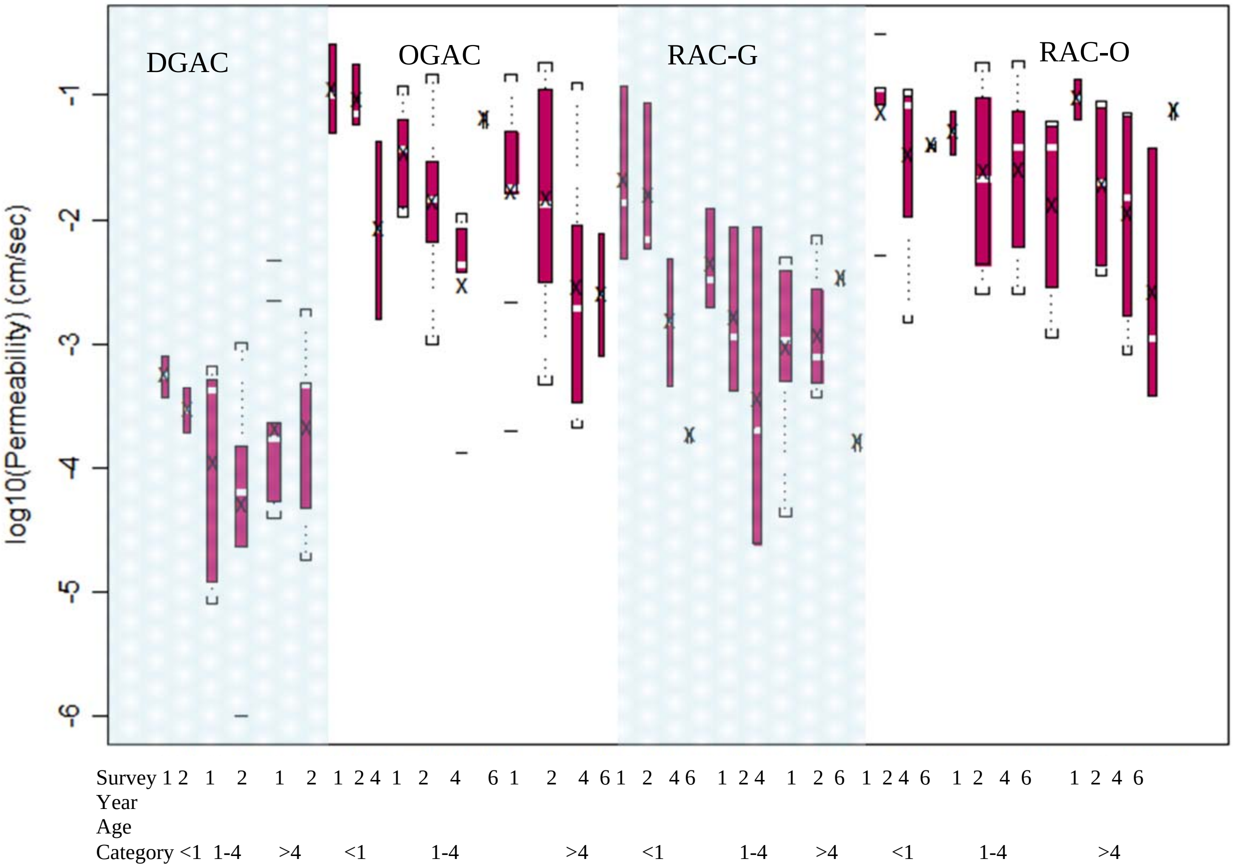




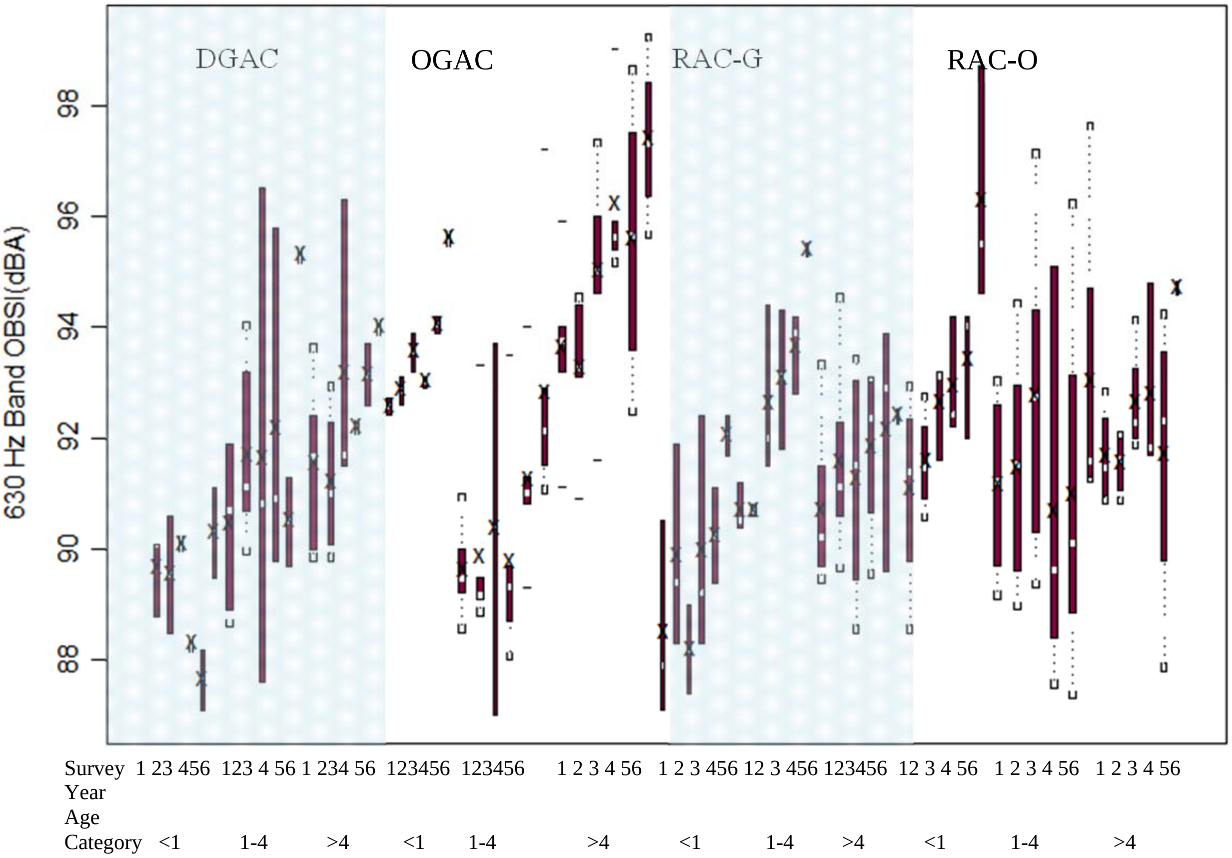


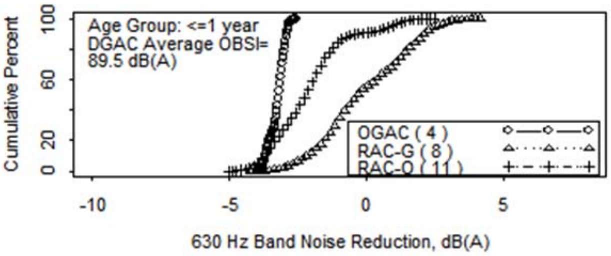


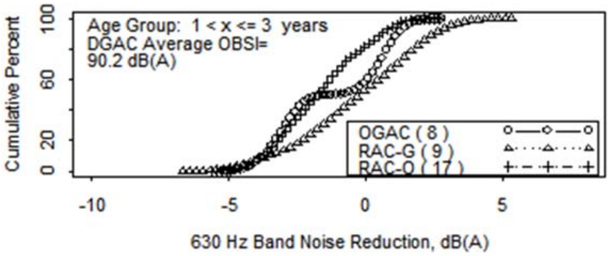

DGAC
log10(Permeability) (cm/s)
Age (year)
01-N114
06-N434
ES-09
QP-06
QP-07
QP-09
QP-15
QP-16
QP-21
QP-30
QP-40
QP-43
RAC-G
ES-12
ES-13
QP-02
QP-05
QP-14
QP-18
QP-19
QP-26
QP-31
QP-33
QP-39
QP-46
OGAC
01-N103
01-N104
01-N105
ES-01
ES-02
ES-03
ES-04
ES-11
QP-03
QP-04
QP-13
QP-20
QP-22
QP-23
QP-28
QP-29
QP-44
QP-45
RAC-O
06-N466
ES-05
ES-06
ES-21
ES-22
ES-23
QP-01
QP-08
QP-12
QP-17
QP-24
QP-32
QP-34
QP-35
QP-36
QP-41
QP-51
0
-2
-4
-6
-8
-10
0
5
10
15
20

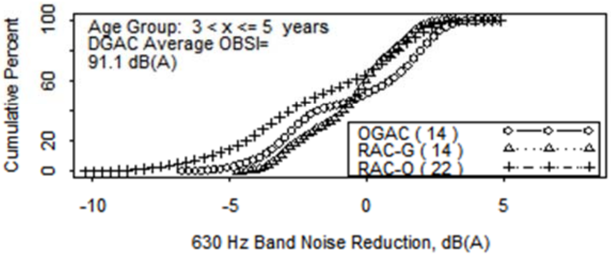

DGAC
OGAC
RAC-G
RAC-O
log10(Permeability) (cm/sec)
-1
-2
-3
-4
-5
-6
Survey 1 2 1 2 1 2 1 2 4 1 2 4 6 1 2 4 6 1 2 4 6 1 2 4 1 2 6 1 2 4 6 1 2 4 6 1 2 4 6
Year
Age
Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

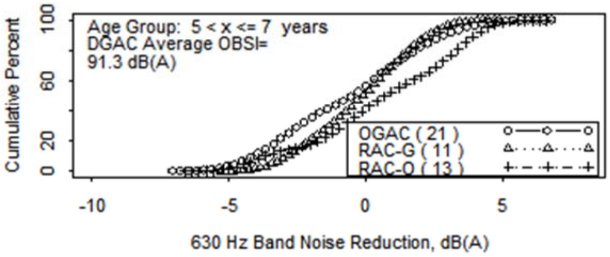
Appendix B.4: Box Plots and Cumulative Distribution of Noise Reduction for Sound Intensity at Frequency Bands not Included in the Analysis

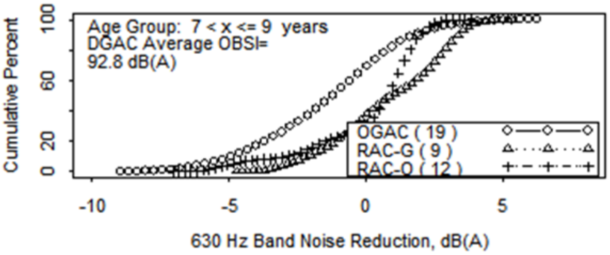


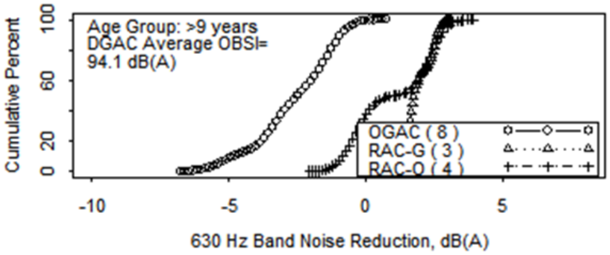

Age Group: <=1 year
DGAC Average OBSI=
89.5 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Cumulative Percent
0
20
60
100
-10
-5
0
5
630 Hz Band Noise Reduction, dB(A)

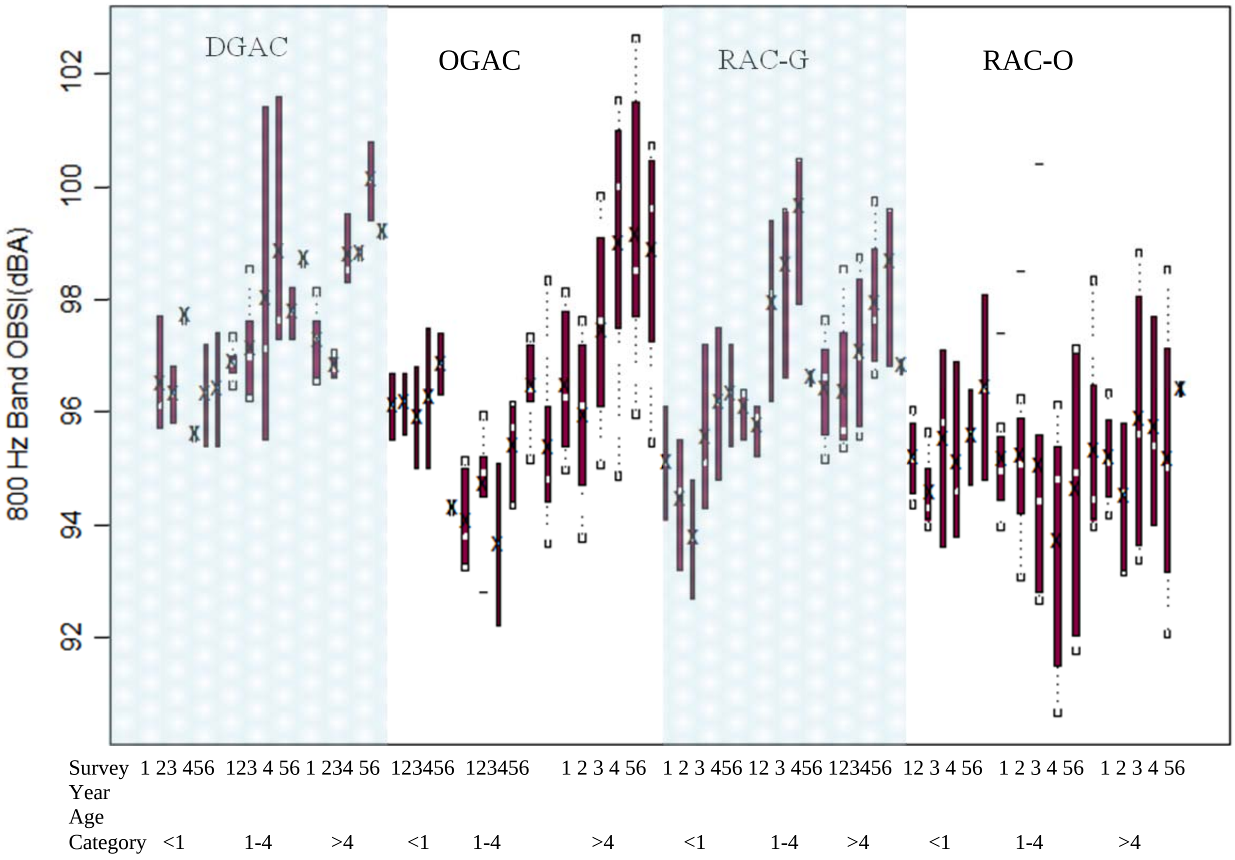

Age Group: 1 < x <= 3 years
DGAC Average OBSI=
90.2 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Cumulative Percent
0
20
60
100
-10
-5
0
5
630 Hz Band Noise Reduction, dB(A)

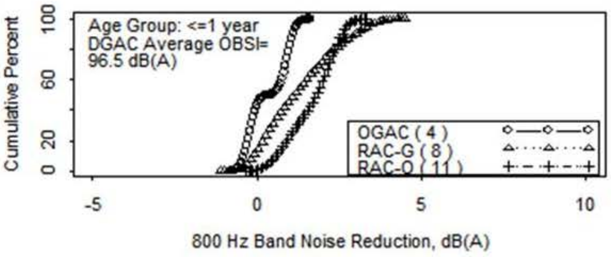

Age Group: 3 < x <= 5 years
DGAC Average OBSI=
91.1 dB(A)
OGAC (14)
RAC-G (14)
RAC-O (22)
Cumulative Percent
0
20
60
100
-10
-5
0
5
630 Hz Band Noise Reduction, dB(A)

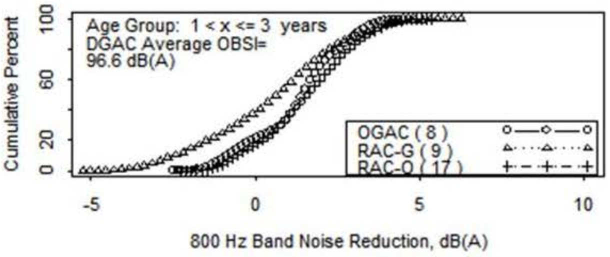

Age Group: 5 < x <= 7 years
DGAC Average OBSI=
91.3 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (13)
Cumulative Percent
0
20
60
100
-10
-5
0
5
630 Hz Band Noise Reduction, dB(A)

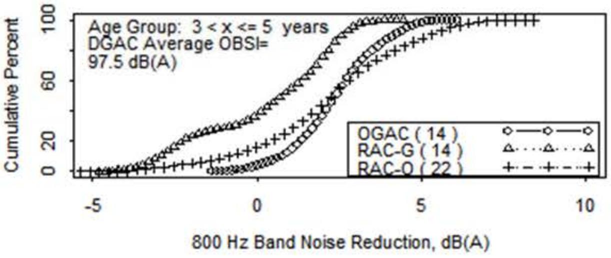

Age Group: 7 < x <= 9 years
DGAC Average OBSI=
92.8 dB(A)
OGAC (19)
RAC-G (9)
RAC-O (12)
Cumulative Percent
0
20
60
100
-10
-5
0
5
630 Hz Band Noise Reduction, dB(A)

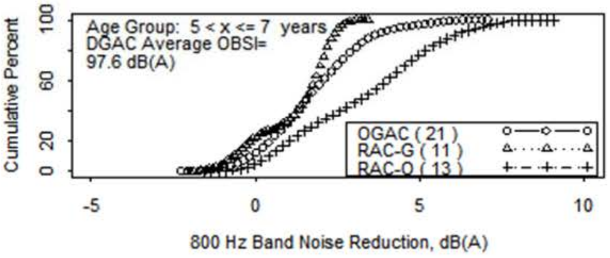

Age Group: >9 years
DGAC Average OBSI=
94.1 dB(A)
OGAC (8)
RAC-G (3)
RAC-O (4)
Cumulative Percent
0
20
60
100
-10
-5
0
5
630 Hz Band Noise Reduction, dB(A)

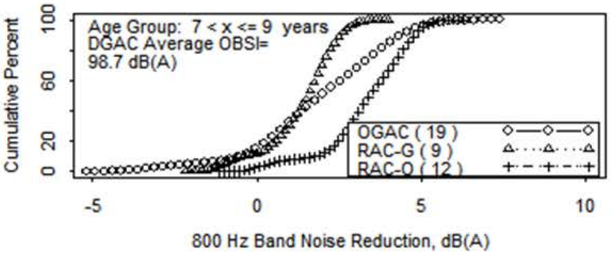

DGAC
OGAC
RAC-G
RAC-O
800 Hz Band OBSI(dBA)
92
94
96
98
100
102
Survey Year 1 23 456 123 4 56 1 234 56 123456 123456 1 2 3 4 56 1 2 3 456 12 3 456 123456 12 3 4 56 1 2 3 4 56 1 2 3 4 56
Age Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

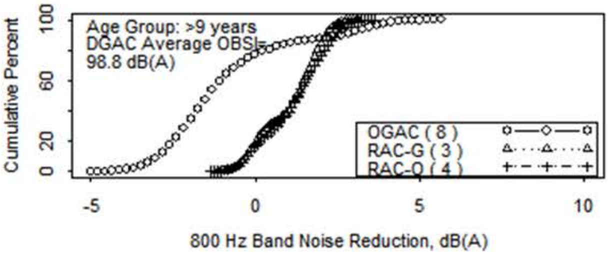

Age Group: <=1 year
DGAC Average OBSI=
96.5 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Cumulative Percent
0
20
60
100
-5
0
5
10
800 Hz Band Noise Reduction, dB(A)

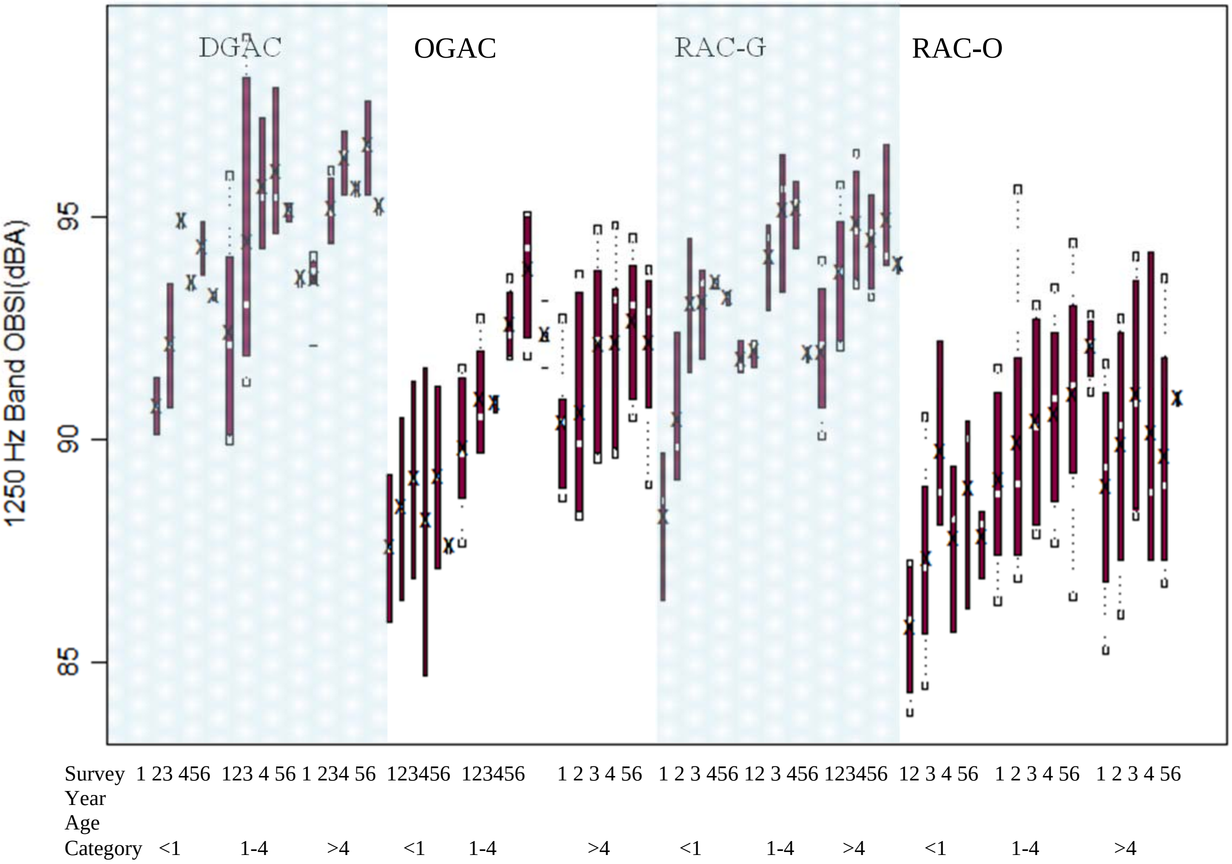

Age Group: 1 < x <= 3 years
DGAC Average OBSI=
96.6 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Cumulative Percent
0
20
60
100
-5
0
5
10
800 Hz Band Noise Reduction, dB(A)

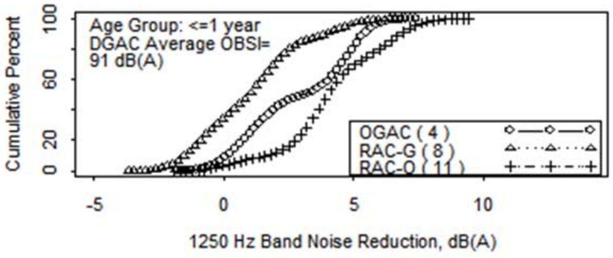

Age Group: 3 < x <= 5 years
DGAC Average OBSI=
97.5 dB(A)
OGAC (14)
RAC-G (14)
RAC-O (22)
Cumulative Percent
0
20
60
100
-5
0
5
10
800 Hz Band Noise Reduction, dB(A)

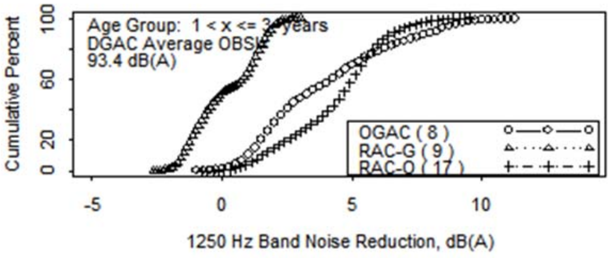

Age Group: 5 < x <= 7 years
DGAC Average OBSI=
97.6 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (13)
Cumulative Percent
0
20
60
100
-5
0
5
10
800 Hz Band Noise Reduction, dB(A)

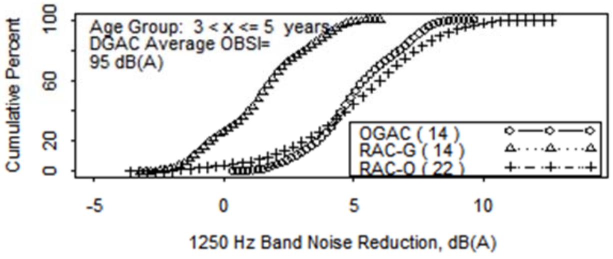

Age Group: 7 < x <= 9 years
DGAC Average OBSI=
98.7 dB(A)
OGAC (19)
RAC-G (9)
RAC-O (12)
Cumulative Percent
0
20
60
100
-5
0
5
10
800 Hz Band Noise Reduction, dB(A)

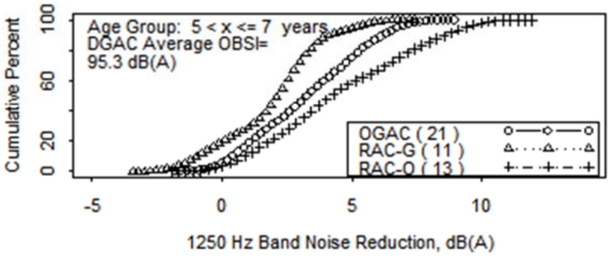

Age Group: >9 years
DGAC Average OBSI=
98.8 dB(A)
OGAC (8)
RAC-G (3)
RAC-O (4)
Cumulative Percent
0
20
60
100
-5
0
5
10
800 Hz Band Noise Reduction, dB(A)

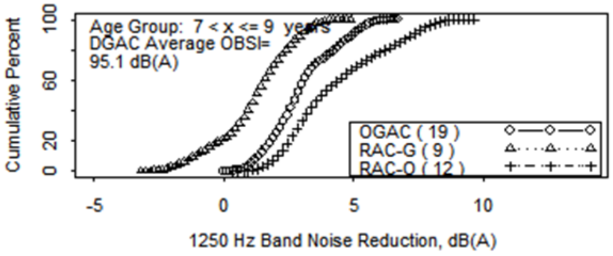

DGAC
OGAC
RAC-G
RAC-O
1250 Hz Band OBSI(dBA)
85
90
95
Survey 1 23 456 123 4 56 1 234 56 123456 123456 1 2 3 4 56 1 2 3 456 12 3 456 123456 12 3 4 56 1 2 3 4 56 1 2 3 4 56
Year
Age
Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

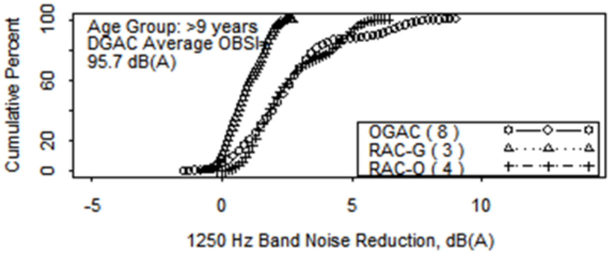

Age Group: <=1 year
DGAC Average OBSI=
91 dB(A)
Cumulative Percent
0
20
60
100
-5
0
5
10
1250 Hz Band Noise Reduction, dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)

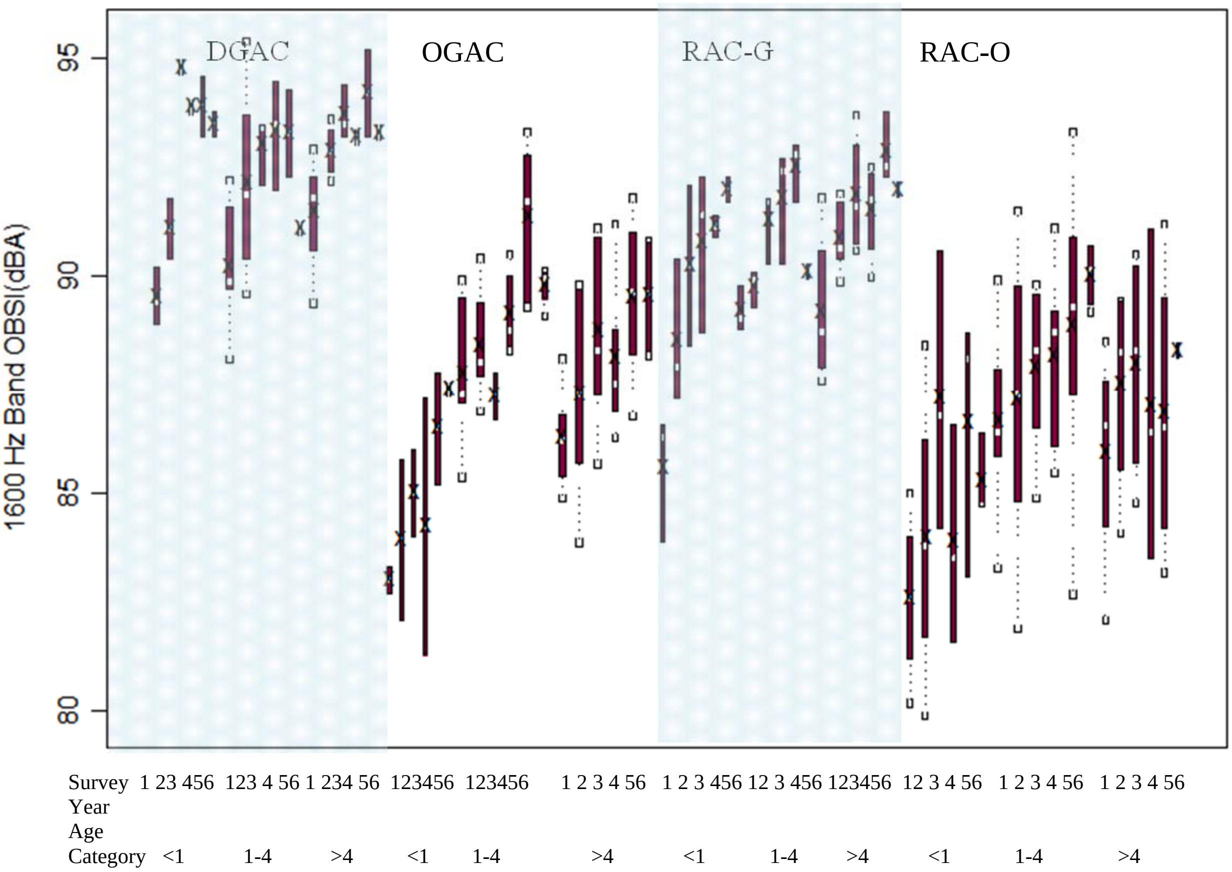

Age Group: 1 < x <= 3 years
DGAC Average OBSI=
93.4 dB(A)
Cumulative Percent
0
20
60
100
-5
0
5
10
1250 Hz Band Noise Reduction, dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)

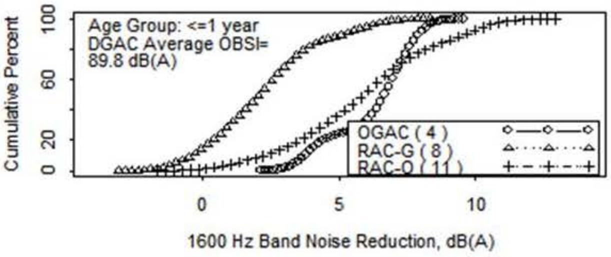

Age Group: 3 < x <= 5 years
DGAC Average OBSI=
95 dB(A)
Cumulative Percent
0
20
60
100
-5
0
5
10
1250 Hz Band Noise Reduction, dB(A)
OGAC (14)
RAC-G (14)
RAC-O (22)

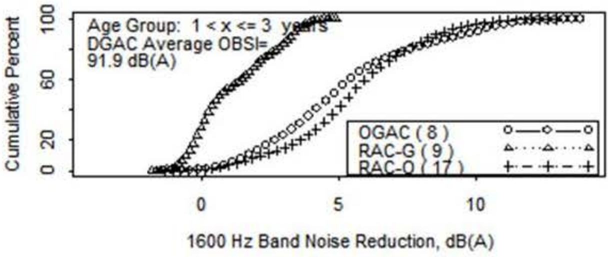

Age Group: 5 < x <= 7 years
DGAC Average OBSI=
95.3 dB(A)
Cumulative Percent
0
20
60
100
-5
0
5
10
1250 Hz Band Noise Reduction, dB(A)
OGAC (21)
RAC-G (11)
RAC-O (13)

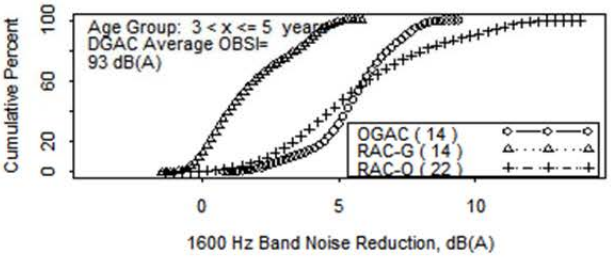

Age Group: 7 < x <= 9 years
DGAC Average OBSI=
95.1 dB(A)
Cumulative Percent
0
20
60
100
-5
0
5
10
1250 Hz Band Noise Reduction, dB(A)
OGAC (19)
RAC-G (9)
RAC-O (12)

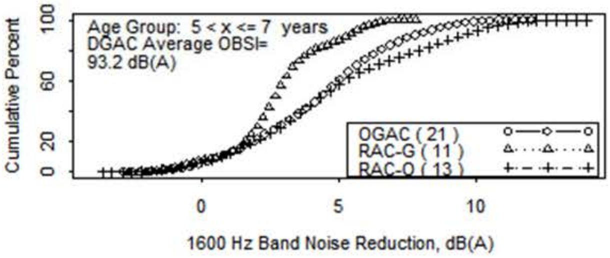

Age Group: >9 years
DGAC Average OBSI=
95.7 dB(A)
Cumulative Percent
0
20
60
100
-5
0
5
10
1250 Hz Band Noise Reduction, dB(A)
OGAC (8)
RAC-G (3)
RAC-O (4)

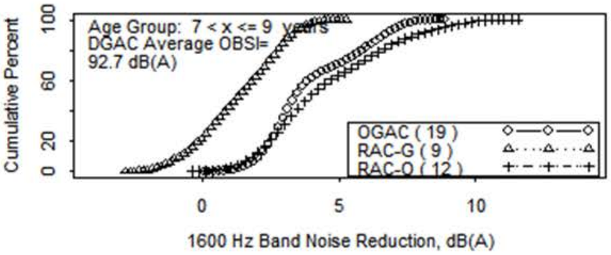

1600 Hz Band OBSI(dBA)
95
90
85
80
DGAC
OGAC
RAC-G
RAC-O
Survey 1 23 456 123 4 56 1 234 56 123456 123456 1 2 3 4 56 1 2 3 456 12 3 456 123456 12 3 4 56 1 2 3 4 56 1 2 3 4 56
Year
Age
Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

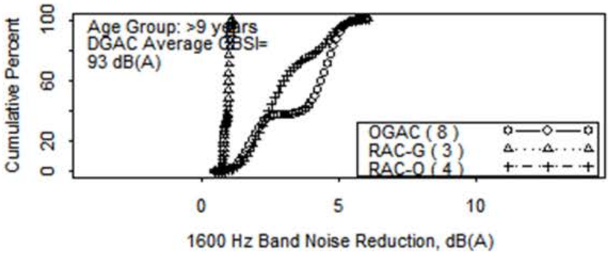

Age Group: <=1 year
DGAC Average OBSI=
89.8 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Cumulative Percent
0
20
60
100
0
5
10
1600 Hz Band Noise Reduction, dB(A)

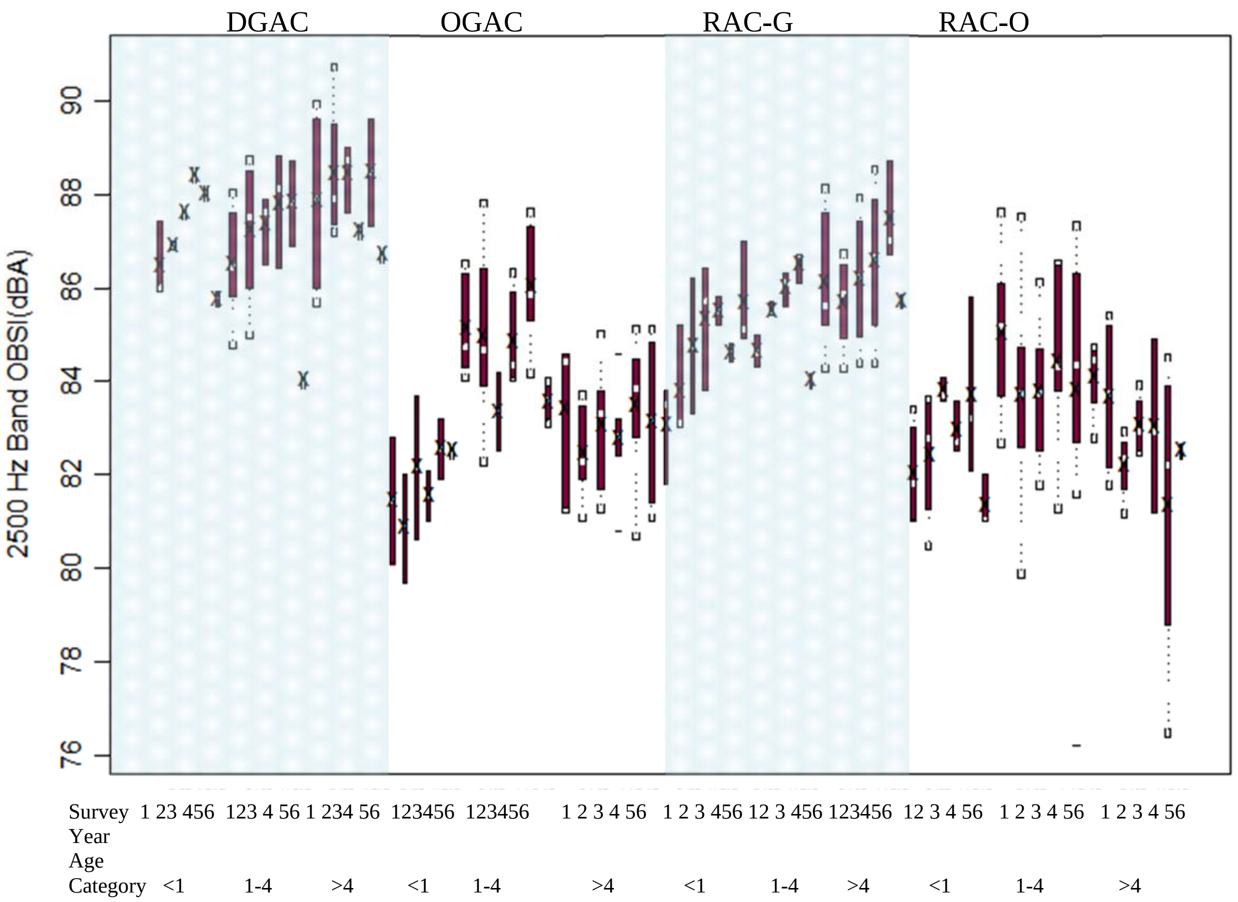

Age Group: 1 < x <= 3 years
DGAC Average OBSI=
91.9 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Cumulative Percent
0
20
60
100
0
5
10
1600 Hz Band Noise Reduction, dB(A)

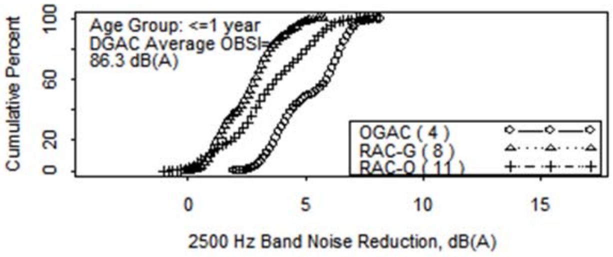

Age Group: 3 < x <= 5 years
DGAC Average OBSI=
93 dB(A)
OGAC (14)
RAC-G (14)
RAC-O (22)
Cumulative Percent
0
20
60
100
0
5
10
1600 Hz Band Noise Reduction, dB(A)

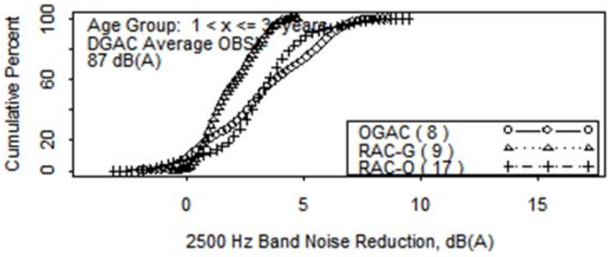

Age Group: 5 < x <= 7 years
DGAC Average OBSI=
93.2 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (13)
Cumulative Percent
0
20
60
100
0
5
10
1600 Hz Band Noise Reduction, dB(A)

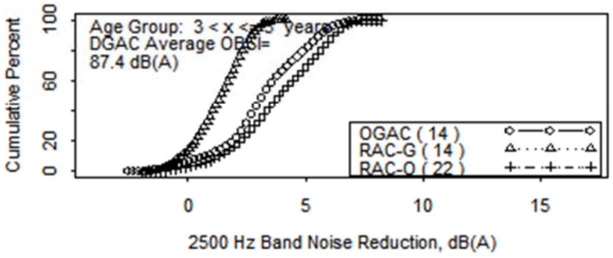

Age Group: 7 < x <= 9 years
DGAC Average OBSI=
92.7 dB(A)
OGAC (19)
RAC-G (9)
RAC-O (12)
Cumulative Percent
0
20
60
100
0
5
10
1600 Hz Band Noise Reduction, dB(A)

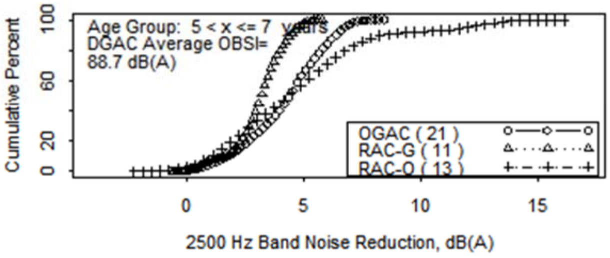

Age Group: >9 years
DGAC Average OBSI=
93 dB(A)
OGAC (8)
RAC-G (3)
RAC-O (4)
Cumulative Percent
0
20
60
100
0
5
10
1600 Hz Band Noise Reduction, dB(A)

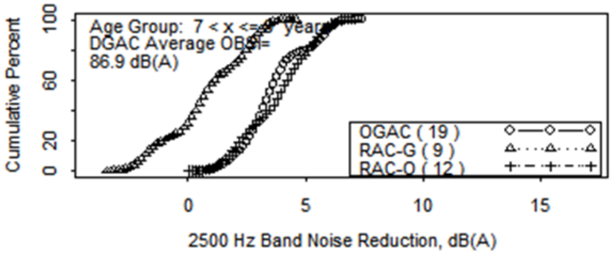

DGAC
OGAC
RAC-G
RAC-O
2500 Hz Band OBSI(dBA)
90
88
86
84
82
80
78
76
Survey 1 23 456 123 4 56 1 234 56 123456 123456 1 2 3 4 56 1 2 3 456 12 3 456 123456 12 3 4 56 1 2 3 4 56 1 2 3 4 56
Year
Age
Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

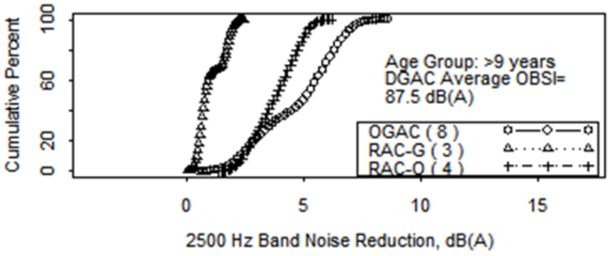

Age Group: <=1 year
DGAC Average OBSI=
86.3 dB(A)
Cumulative Percent
0
20
60
100
OGAC (4)
RAC-G (8)
RAC-O (11)
0
5
10
15
2500 Hz Band Noise Reduction, dB(A)

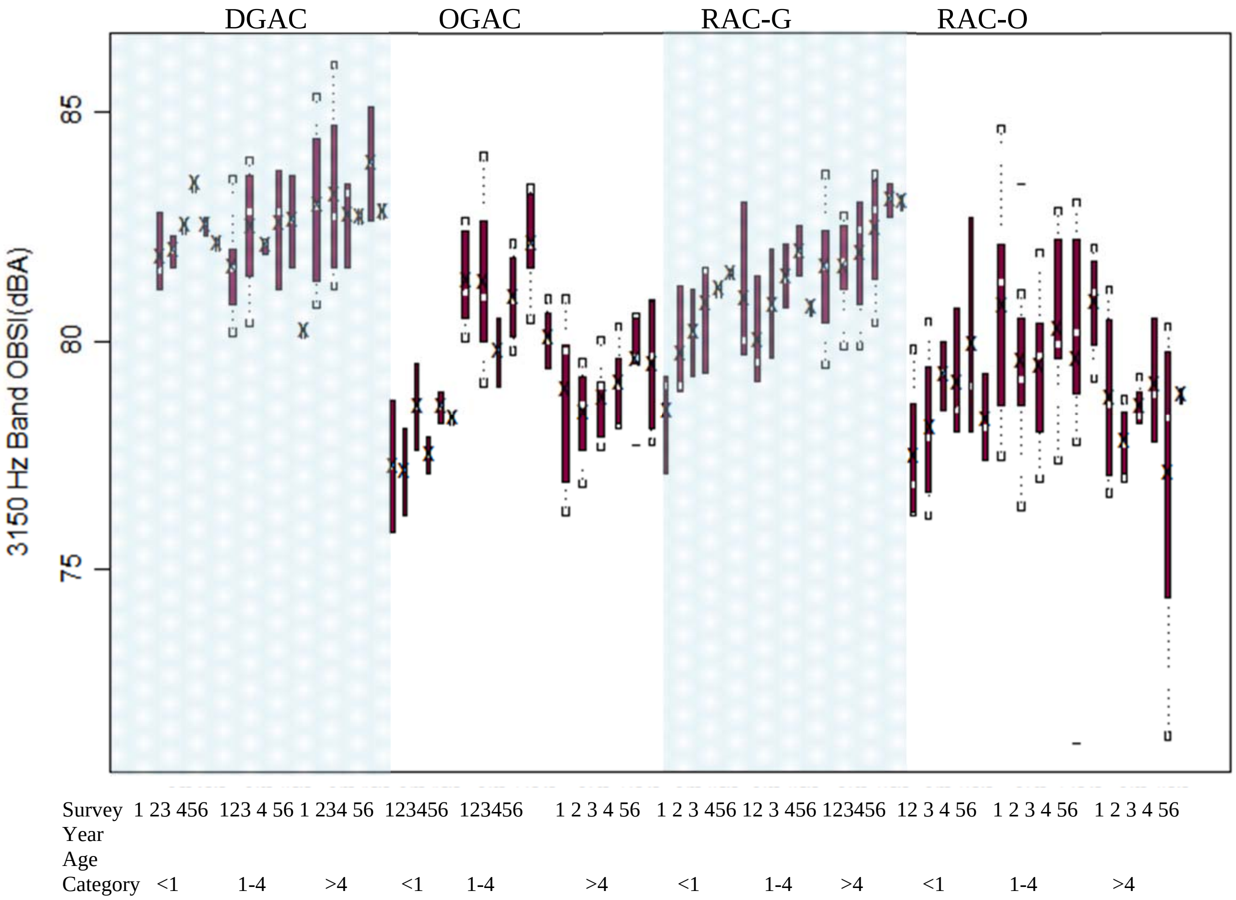

Age Group: 1 < x <= 3 years
DGAC Average OBSI=
87 dB(A)
Cumulative Percent
0
20
60
100
OGAC (8)
RAC-G (9)
RAC-O (17)
0
5
10
15
2500 Hz Band Noise Reduction, dB(A)

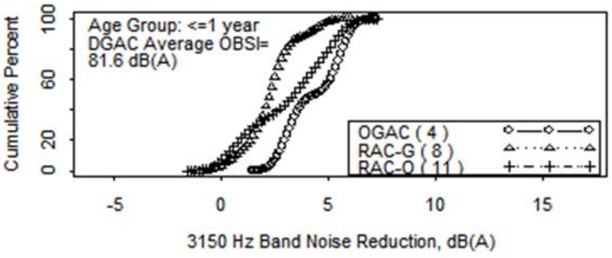

Age Group: 3 < x <= 5 years
DGAC Average OBSI=
87.4 dB(A)
Cumulative Percent
0
20
60
100
OGAC (14)
RAC-G (14)
RAC-O (22)
0
5
10
15
2500 Hz Band Noise Reduction, dB(A)

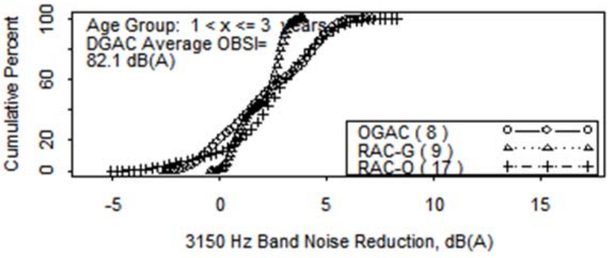

Age Group: 5 < x <= 7 years
DGAC Average OBSI=
88.7 dB(A)
Cumulative Percent
0
20
60
100
OGAC (21)
RAC-G (11)
RAC-O (13)
0
5
10
15
2500 Hz Band Noise Reduction, dB(A)

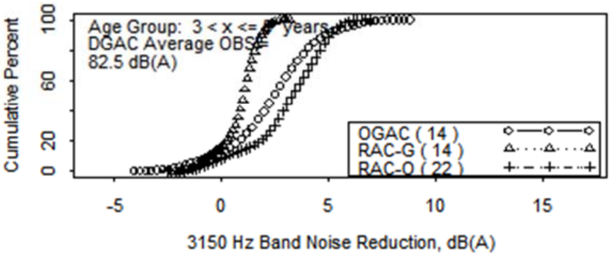

Age Group: 7 < x <= 9 years
DGAC Average OBSI=
86.9 dB(A)
Cumulative Percent
0
20
60
100
OGAC (19)
RAC-G (9)
RAC-O (12)
0
5
10
15
2500 Hz Band Noise Reduction, dB(A)

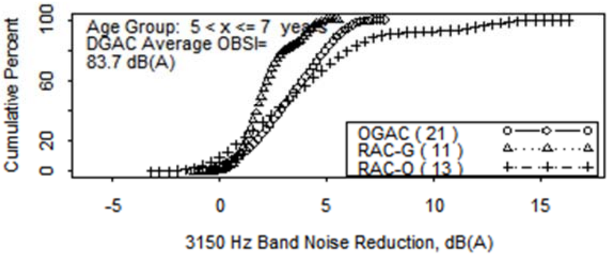

Age Group: >9 years
DGAC Average OBSI=
87.5 dB(A)
Cumulative Percent
0
20
60
100
OGAC (8)
RAC-G (3)
RAC-O (4)
0
5
10
15
2500 Hz Band Noise Reduction, dB(A)

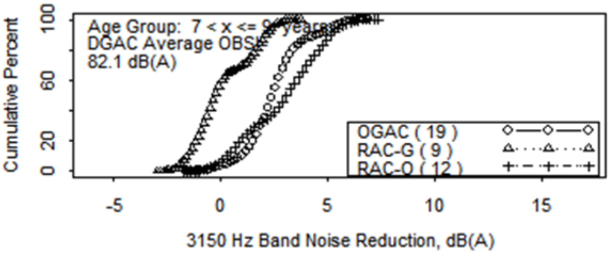

DGAC
OGAC
RAC-G
RAC-O
85
80
75
3150 Hz Band OBSI(dBA)
Survey Year
1 23 456 123 4 56 1 234 56 123456 123456 1 2 3 4 56 1 2 3 456 12 3 456 123456 12 3 4 56 1 2 3 4 56 1 2 3 4 56
Age Category
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

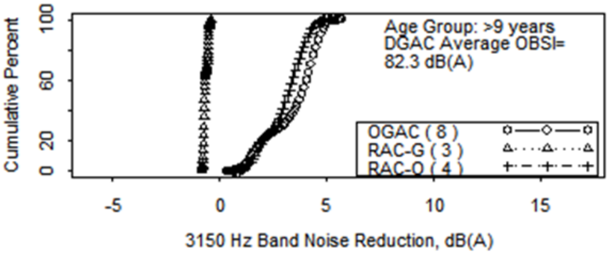

Age Group: <=1 year
DGAC Average OBSI=
81.6 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
3150 Hz Band Noise Reduction, dB(A)

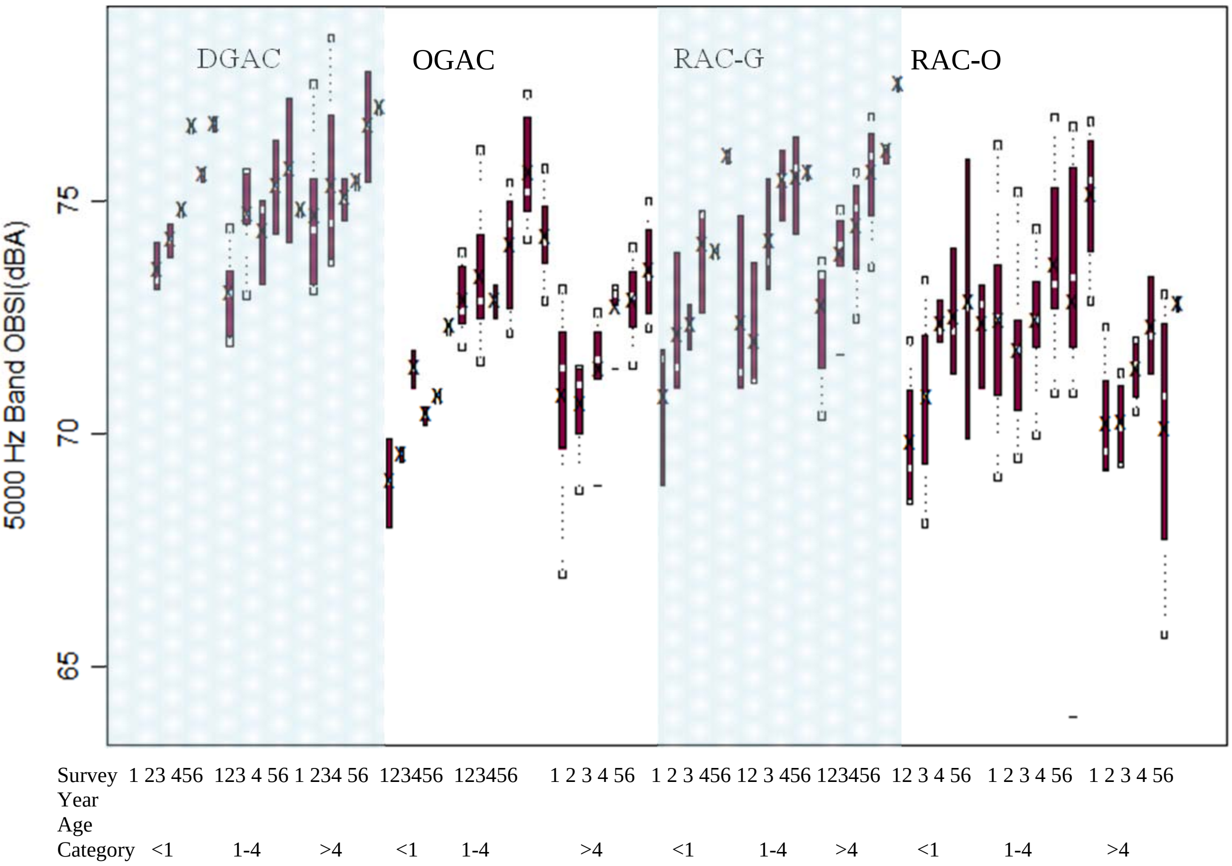

Age Group: 1 < x <= 3 years
DGAC Average OBSI=
82.1 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
3150 Hz Band Noise Reduction, dB(A)

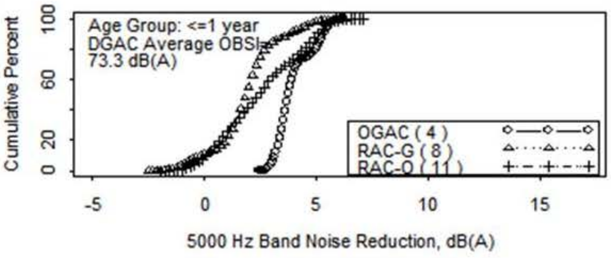

Age Group: 3 < x <= years
DGAC Average OBSI=
82.5 dB(A)
OGAC (14)
RAC-G (14)
RAC-O (22)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
3150 Hz Band Noise Reduction, dB(A)

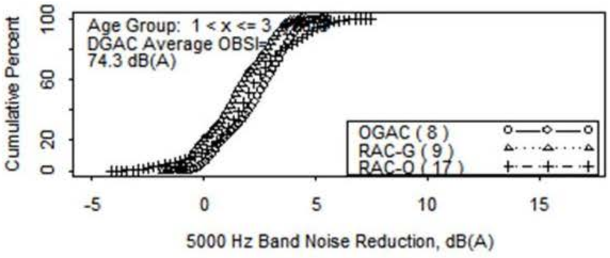

Age Group: 5 < x <= 7 years
DGAC Average OBSI=
83.7 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (13)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
3150 Hz Band Noise Reduction, dB(A)

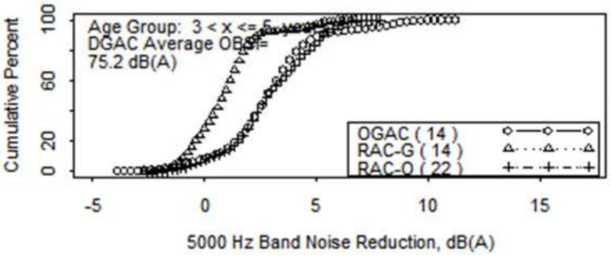

Age Group: 7 < x <= 9 years
DGAC Average OBSI=
82.1 dB(A)
OGAC (19)
RAC-G (9)
RAC-O (12)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
3150 Hz Band Noise Reduction, dB(A)

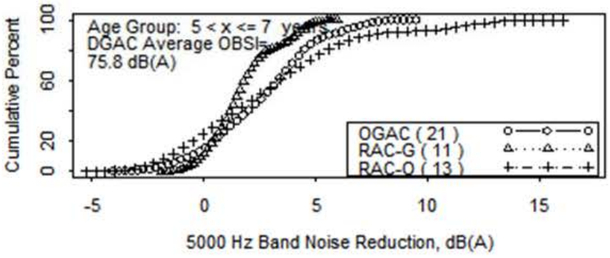

Age Group: >9 years
DGAC Average OBSI=
82.3 dB(A)
OGAC (8)
RAC-G (3)
RAC-O (4)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
3150 Hz Band Noise Reduction, dB(A)

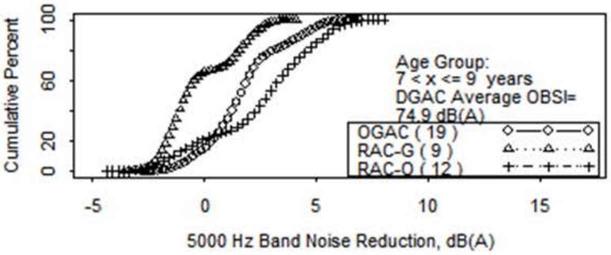

DGAC
OGAC
RAC-G
RAC-O
5000 Hz Band OBSI(dBA)
75
70
65
Survey 1 23 456 123 4 56 1 234 56 123456 123456 1 2 3 4 56 1 2 3 456 12 3 456 123456 12 3 4 56 1 2 3 4 56 1 2 3 4 56
Year
Age
Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

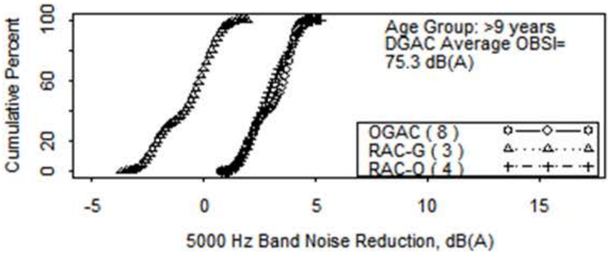

Age Group: <=1 year
DGAC Average OBSI=
73.3 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
5000 Hz Band Noise Reduction, dB(A)


Age Group: 1 < x <= 3
DGAC Average OBSI=
74.3 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
5000 Hz Band Noise Reduction, dB(A)

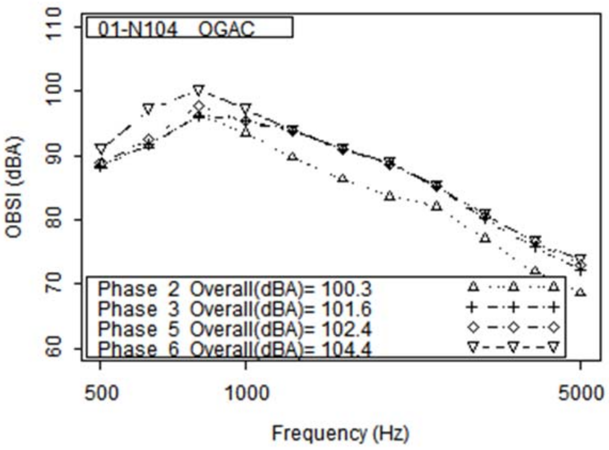

Age Group: 3 < x <= 5
DGAC Average OBSI=
75.2 dB(A)
OGAC (14)
RAC-G (14)
RAC-O (22)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
5000 Hz Band Noise Reduction, dB(A)

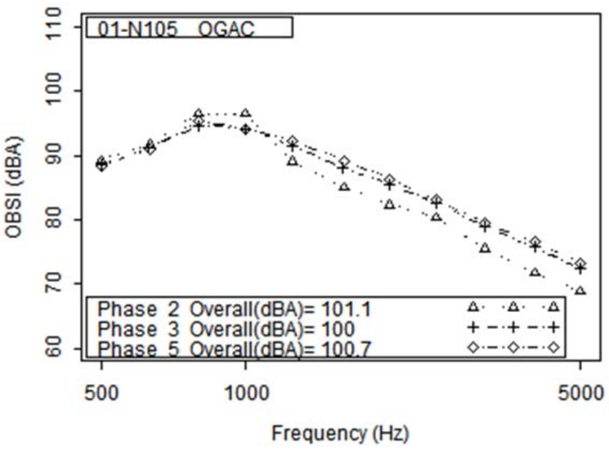

Age Group: 5 < x <= 7 years
DGAC Average OBSI=
75.8 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (13)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
5000 Hz Band Noise Reduction, dB(A)

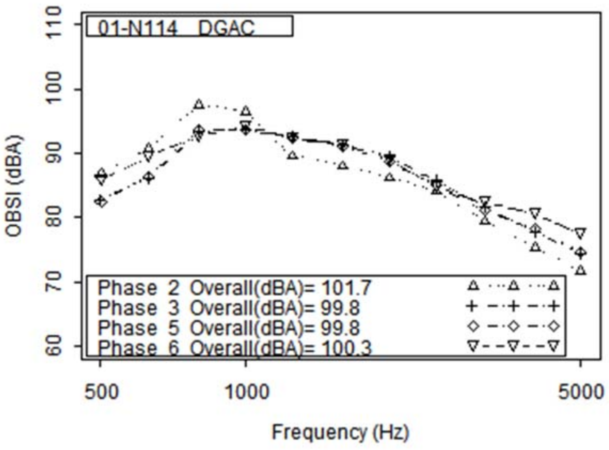

Age Group:
7 < x <= 9 years
DGAC Average OBSI=
74.9 dB(A)
OGAC (19)
RAC-G (9)
RAC-O (12)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
5000 Hz Band Noise Reduction, dB(A)

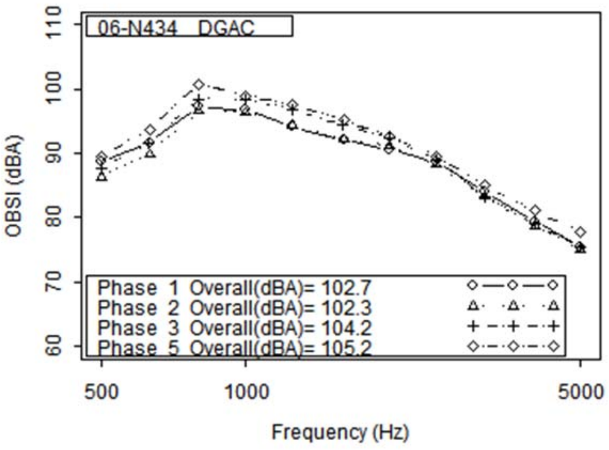

Age Group: >9 years
DGAC Average OBSI=
75.3 dB(A)
OGAC (8)
RAC-G (3)
RAC-O (4)
Cumulative Percent
0
20
60
100
-5
0
5
10
15
5000 Hz Band Noise Reduction, dB(A)

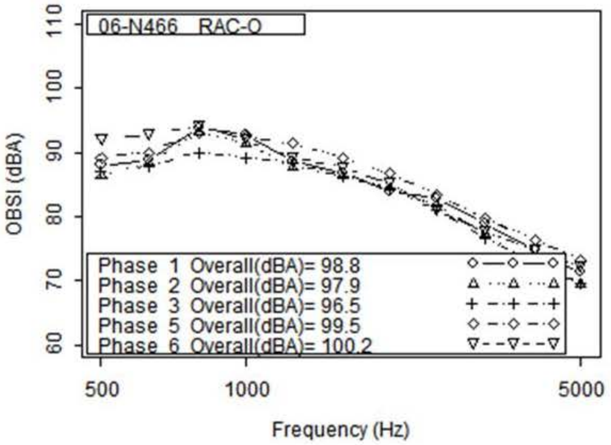
Appendix B.5: Sound Intensity Spectra Measured Over Six Years for Each Pavement Section

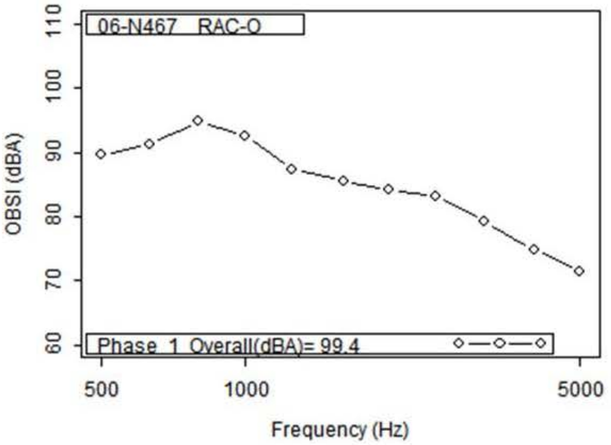


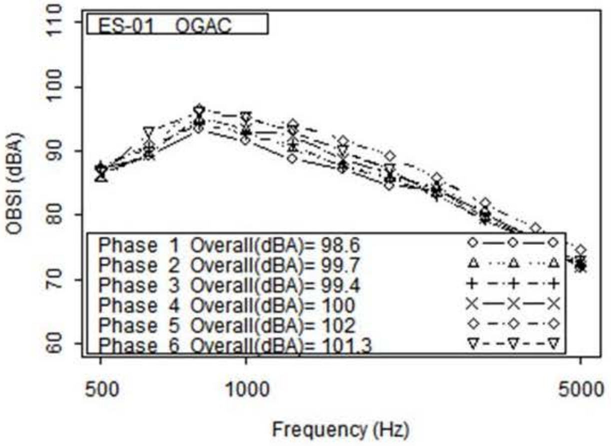


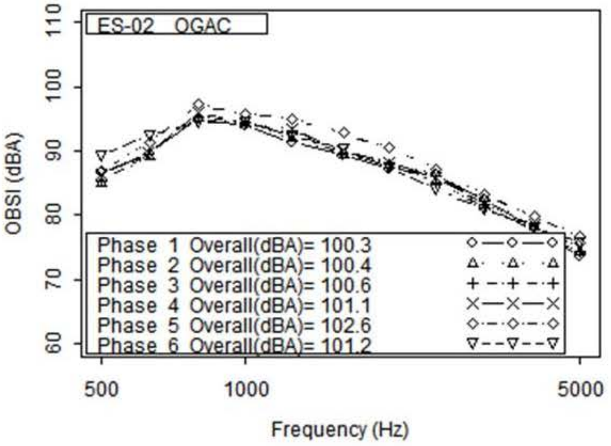


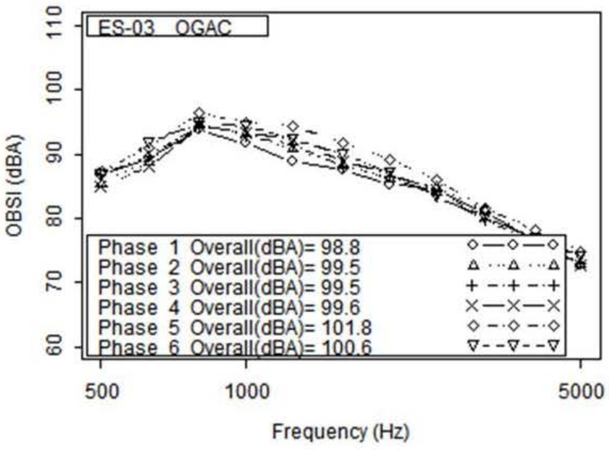


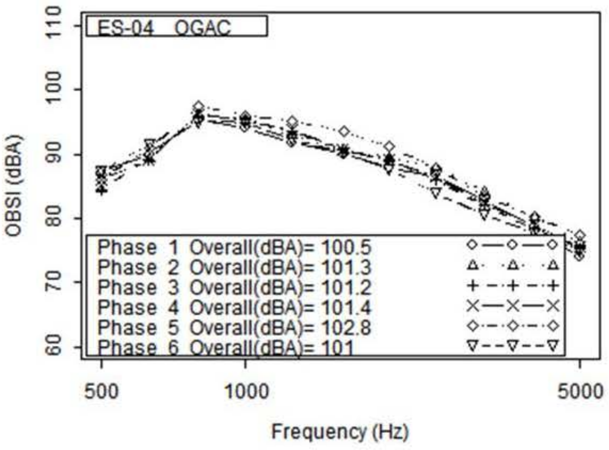

06-N466 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 98.8
Phase 2 Overall(dBA)= 97.9
Phase 3 Overall(dBA)= 96.5
Phase 5 Overall(dBA)= 99.5
Phase 6 Overall(dBA)= 100.2

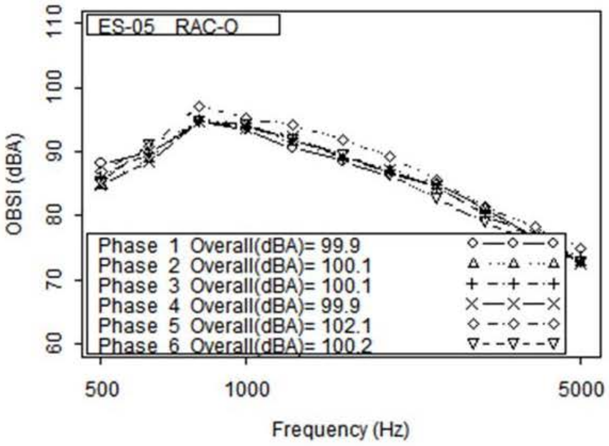

06-N467 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 99.4

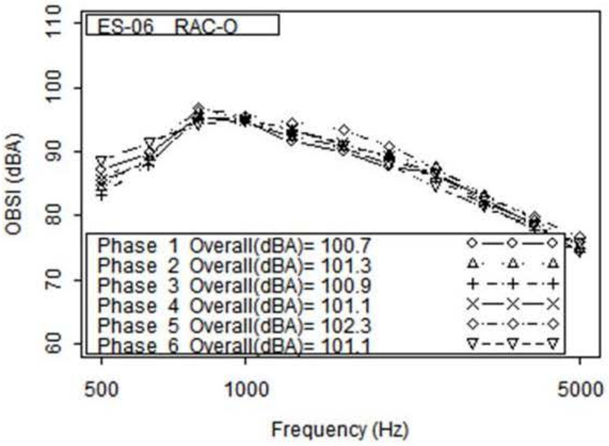

ES-01 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 98.6
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 99.4
Phase 4 Overall(dBA)= 100
Phase 5 Overall(dBA)= 102
Phase 6 Overall(dBA)= 101.3

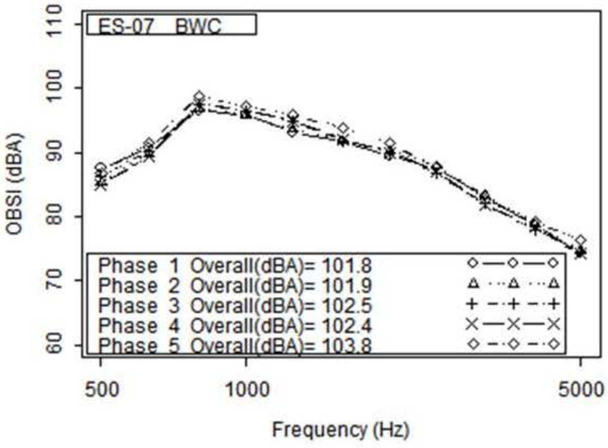

ES-02 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 100.6
Phase 4 Overall(dBA)= 101.1
Phase 5 Overall(dBA)= 102.6
Phase 6 Overall(dBA)= 101.2

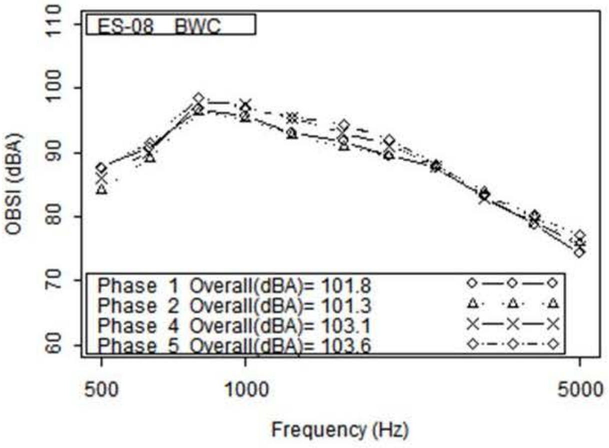

ES-03 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 98.8
Phase 2 Overall(dBA)= 99.5
Phase 3 Overall(dBA)= 99.5
Phase 4 Overall(dBA)= 99.6
Phase 5 Overall(dBA)= 101.8
Phase 6 Overall(dBA)= 100.6

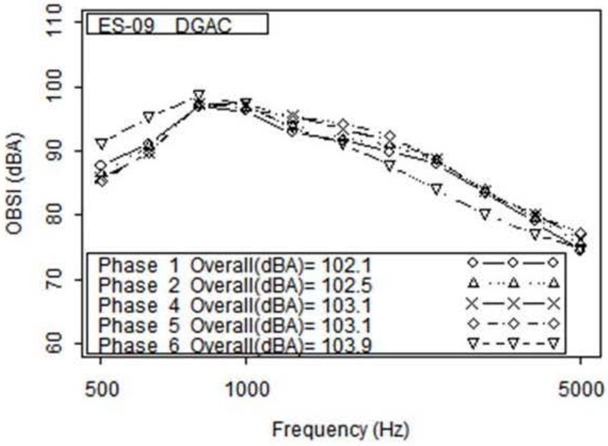

ES-04 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 101.2
Phase 4 Overall(dBA)= 101.4
Phase 5 Overall(dBA)= 102.8
Phase 6 Overall(dBA)= 101

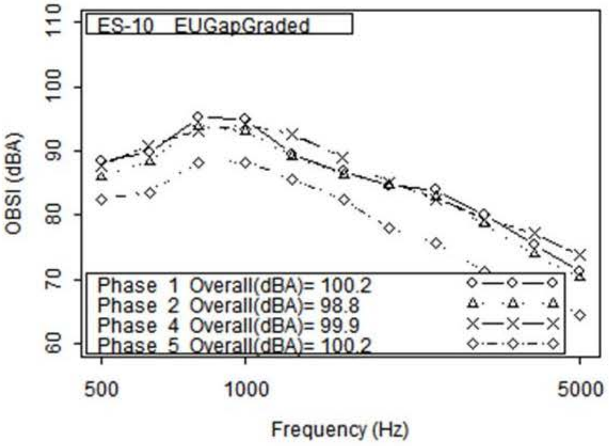

ES-05 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 99.9
Phase 2 Overall(dBA)= 100.1
Phase 3 Overall(dBA)= 100.1
Phase 4 Overall(dBA)= 99.9
Phase 5 Overall(dBA)= 102.1
Phase 6 Overall(dBA)= 100.2

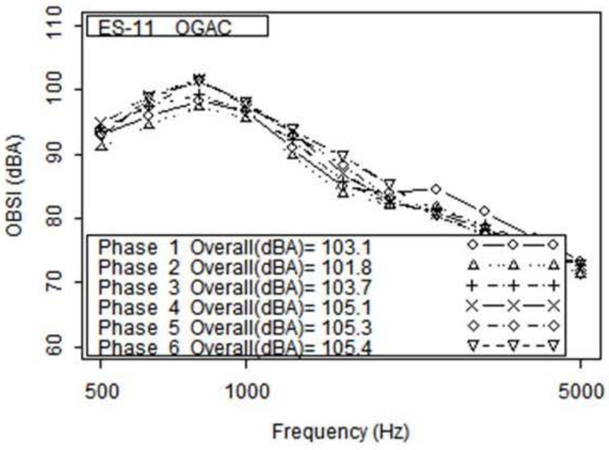

ES-06 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 100.9
Phase 4 Overall(dBA)= 101.1
Phase 5 Overall(dBA)= 102.3
Phase 6 Overall(dBA)= 101.1

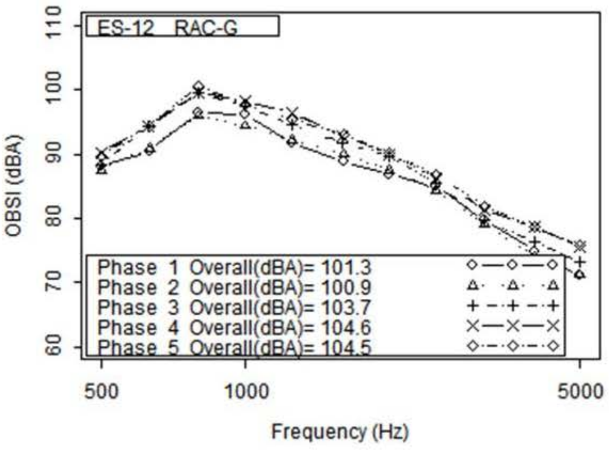

ES-07 BWC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 101.9
Phase 3 Overall(dBA)= 102.5
Phase 4 Overall(dBA)= 102.4
Phase 5 Overall(dBA)= 103.8

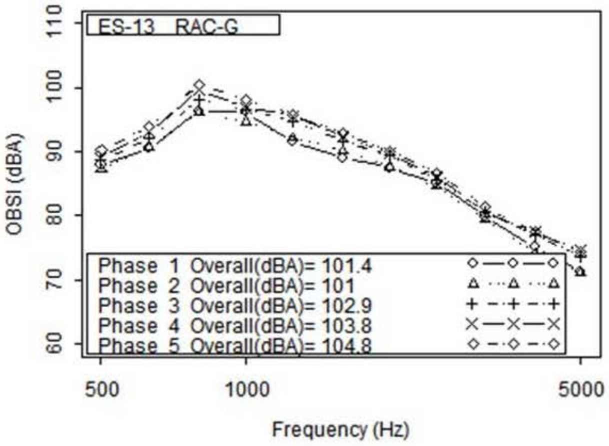

ES-08 BWC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 101.3
Phase 4 Overall(dBA)= 103.1
Phase 5 Overall(dBA)= 103.6

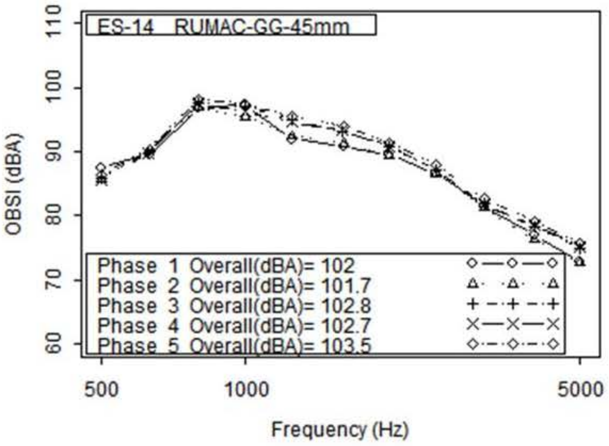

ES-09 DGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102.1
Phase 2 Overall(dBA)= 102.5
Phase 4 Overall(dBA)= 103.1
Phase 5 Overall(dBA)= 103.1
Phase 6 Overall(dBA)= 103.9

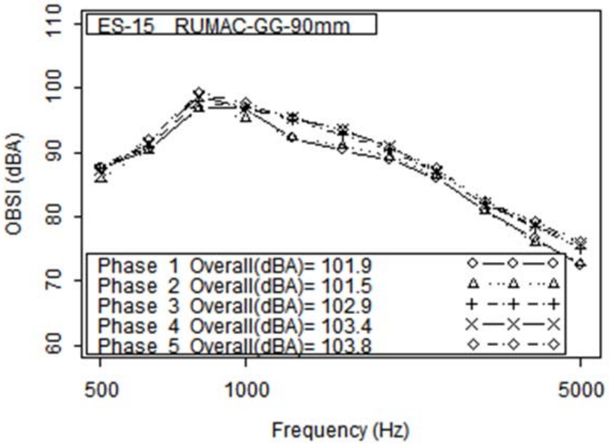

ES-10 EUGapGraded
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 98.8
Phase 4 Overall(dBA)= 99.9
Phase 5 Overall(dBA)= 100.2

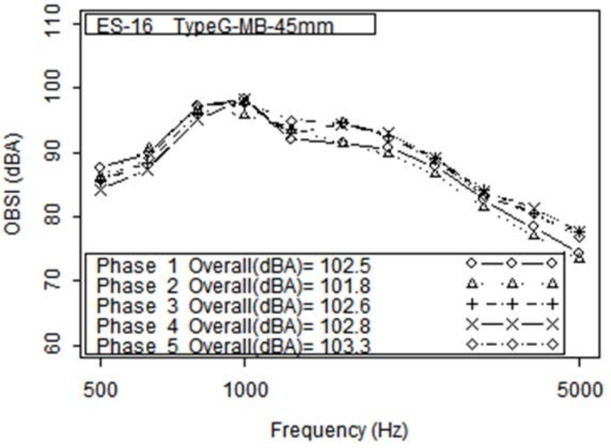

ES-11 OGAC
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 103.1
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 103.7
Phase 4 Overall(dBA)= 105.1
Phase 5 Overall(dBA)= 105.3
Phase 6 Overall(dBA)= 105.4
500
1000
5000
Frequency (Hz)

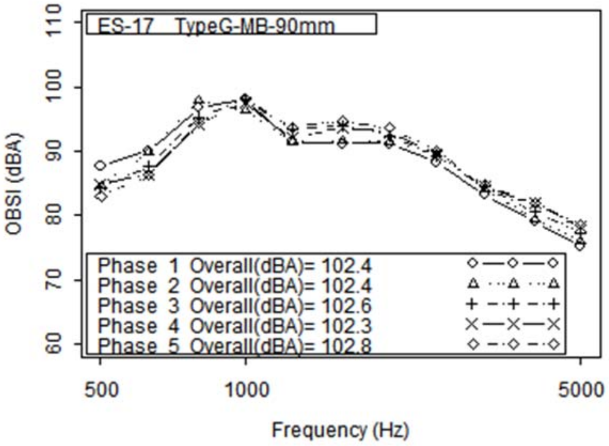

ES-12 RAC-G
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 101.3
Phase 2 Overall(dBA)= 100.9
Phase 3 Overall(dBA)= 103.7
Phase 4 Overall(dBA)= 104.6
Phase 5 Overall(dBA)= 104.5
500
1000
5000
Frequency (Hz)

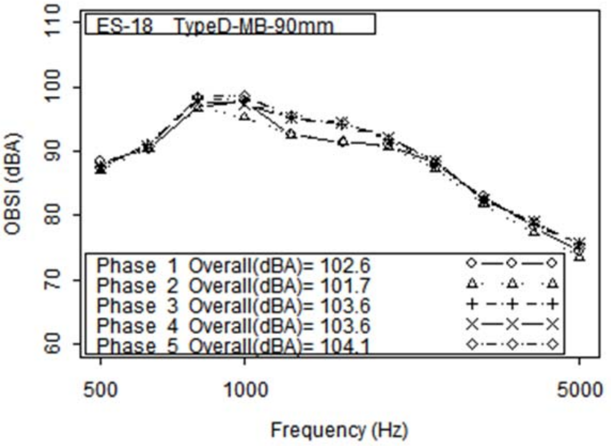

ES-13 RAC-G
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 101
Phase 3 Overall(dBA)= 102.9
Phase 4 Overall(dBA)= 103.8
Phase 5 Overall(dBA)= 104.8
500
1000
5000
Frequency (Hz)

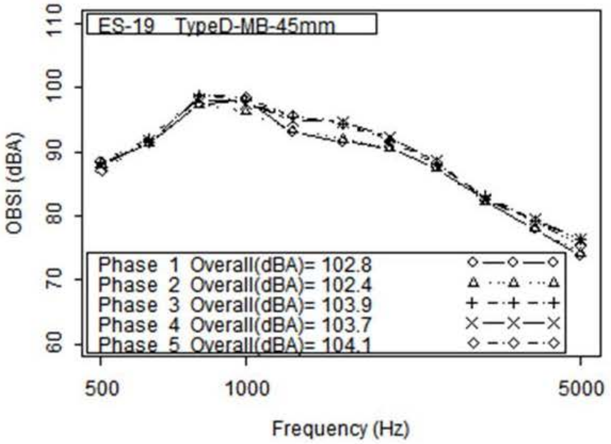

ES-14 RUMAC-GG-45mm
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 101.7
Phase 3 Overall(dBA)= 102.8
Phase 4 Overall(dBA)= 102.7
Phase 5 Overall(dBA)= 103.5
500
1000
5000
Frequency (Hz)

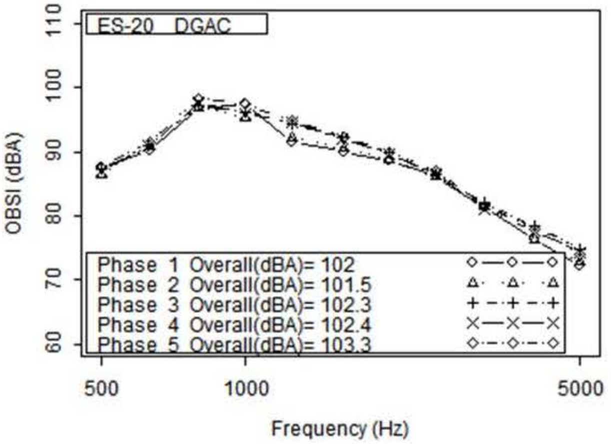

ES-15 RUMAC-GG-90mm
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.9
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 102.9
Phase 4 Overall(dBA)= 103.4
Phase 5 Overall(dBA)= 103.8

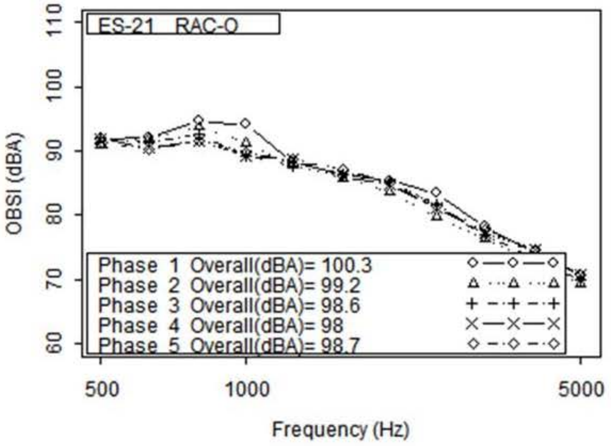

ES-16 TypeG-MB-45mm
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 102.8
Phase 5 Overall(dBA)= 103.3

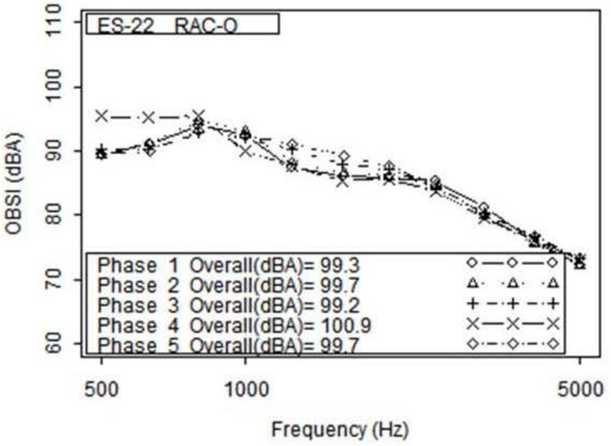

ES-17 TypeG-MB-90mm
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102.4
Phase 2 Overall(dBA)= 102.4
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 102.3
Phase 5 Overall(dBA)= 102.8

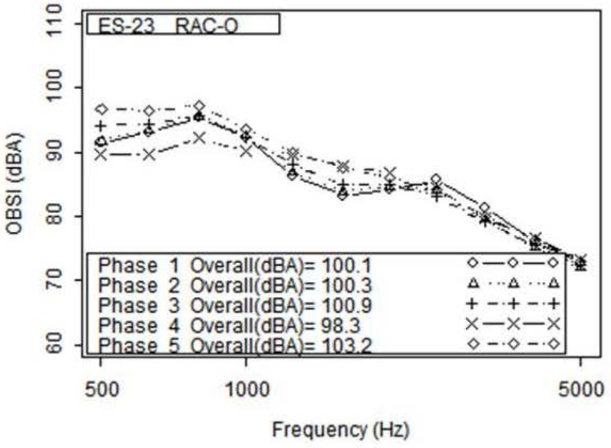

ES-18 TypeD-MB-90mm
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102.6
Phase 2 Overall(dBA)= 101.7
Phase 3 Overall(dBA)= 103.6
Phase 4 Overall(dBA)= 103.6
Phase 5 Overall(dBA)= 104.1

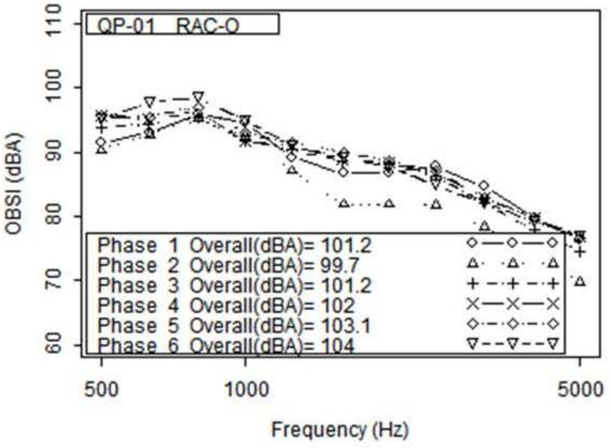

ES-19 TypeD-MB-45mm
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 102.4
Phase 3 Overall(dBA)= 103.9
Phase 4 Overall(dBA)= 103.7
Phase 5 Overall(dBA)= 104.1

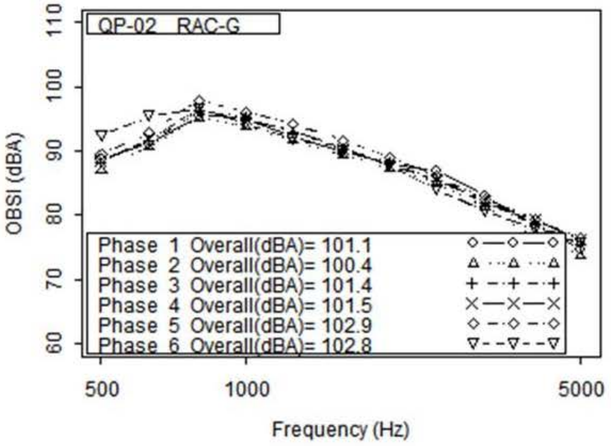

ES-20 DGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 102.3
Phase 4 Overall(dBA)= 102.4
Phase 5 Overall(dBA)= 103.3

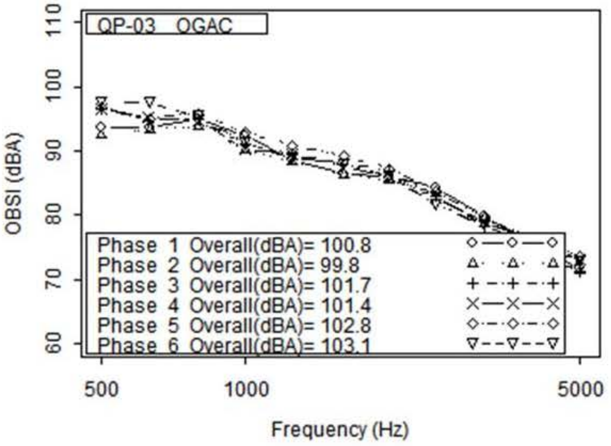

ES-21 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 99.2
Phase 3 Overall(dBA)= 98.6
Phase 4 Overall(dBA)= 98
Phase 5 Overall(dBA)= 98.7

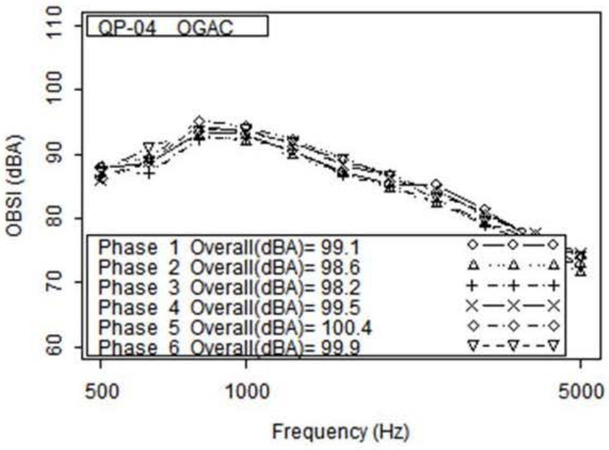

ES-22 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 99.3
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 99.2
Phase 4 Overall(dBA)= 100.9
Phase 5 Overall(dBA)= 99.7

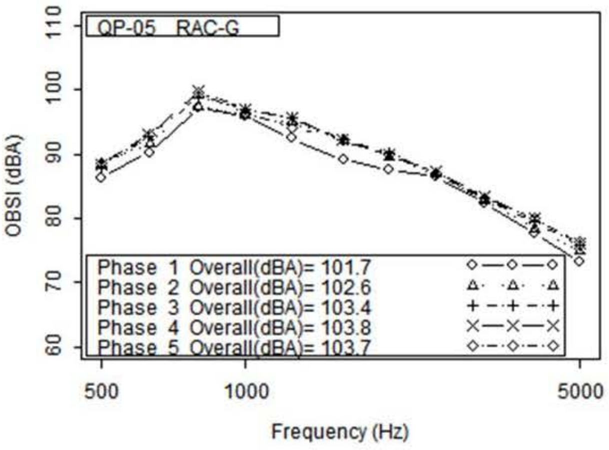

ES-23 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.1
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 100.9
Phase 4 Overall(dBA)= 98.3
Phase 5 Overall(dBA)= 103.2

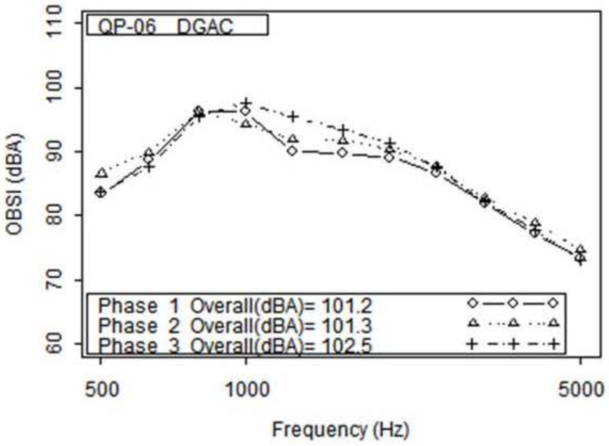

QP-01 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 101.2
Phase 4 Overall(dBA)= 102
Phase 5 Overall(dBA)= 103.1
Phase 6 Overall(dBA)= 104

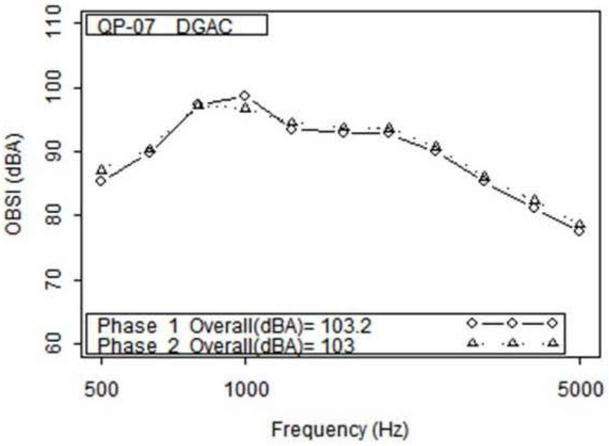

QP-02 RAC-G
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.1
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 101.4
Phase 4 Overall(dBA)= 101.5
Phase 5 Overall(dBA)= 102.9
Phase 6 Overall(dBA)= 102.8

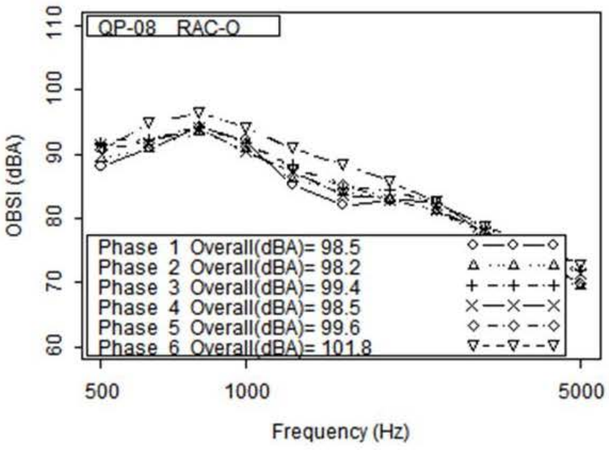

QP-03 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.8
Phase 2 Overall(dBA)= 99.8
Phase 3 Overall(dBA)= 101.7
Phase 4 Overall(dBA)= 101.4
Phase 5 Overall(dBA)= 102.8
Phase 6 Overall(dBA)= 103.1

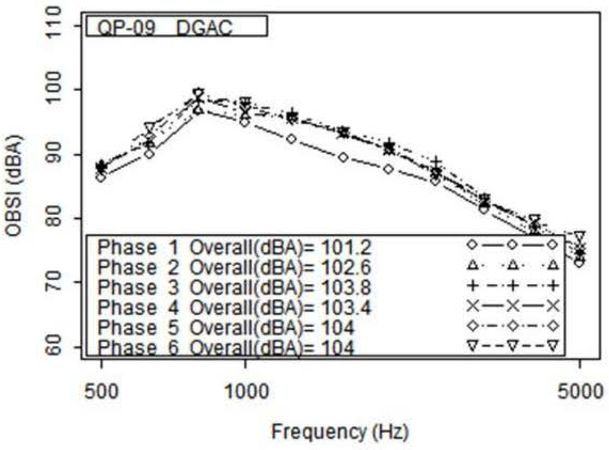

QP-04 OGAC
OBSI (dBA)
Frequency (Hz)
60
70
80
90
100
110
500
1000
5000
Phase 1 Overall(dBA)= 99.1
Phase 2 Overall(dBA)= 98.6
Phase 3 Overall(dBA)= 98.2
Phase 4 Overall(dBA)= 99.5
Phase 5 Overall(dBA)= 100.4
Phase 6 Overall(dBA)= 99.9

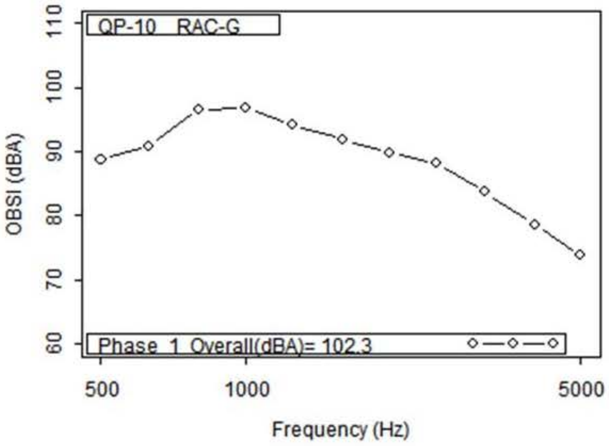

QP-05 RAC-G
OBSI (dBA)
Frequency (Hz)
60
70
80
90
100
110
500
1000
5000
Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.6
Phase 3 Overall(dBA)= 103.4
Phase 4 Overall(dBA)= 103.8
Phase 5 Overall(dBA)= 103.7

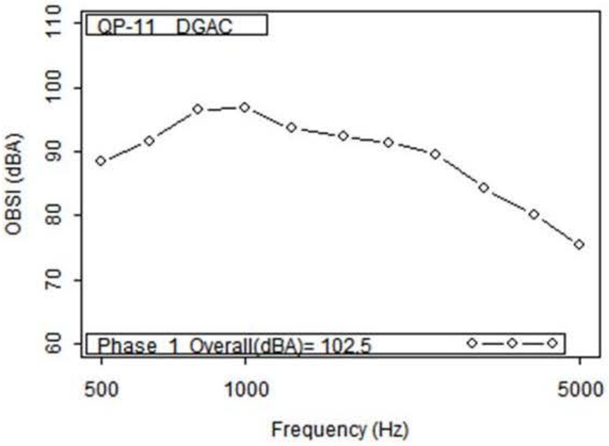

QP-06 DGAC
OBSI (dBA)
Frequency (Hz)
60
70
80
90
100
110
500
1000
5000
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 102.5

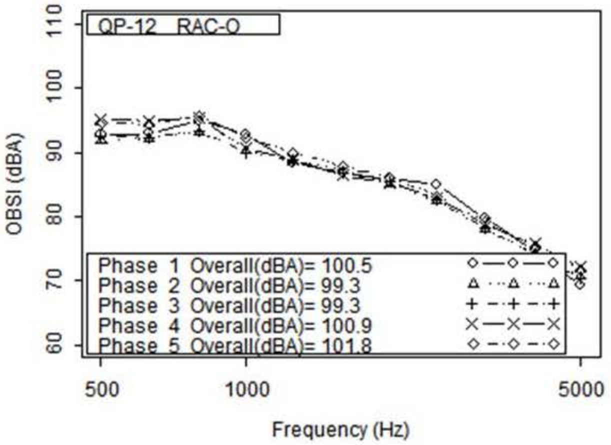

QP-07 DGAC
OBSI (dBA)
Frequency (Hz)
60
70
80
90
100
110
500
1000
5000
Phase 1 Overall(dBA)= 103.2
Phase 2 Overall(dBA)= 103

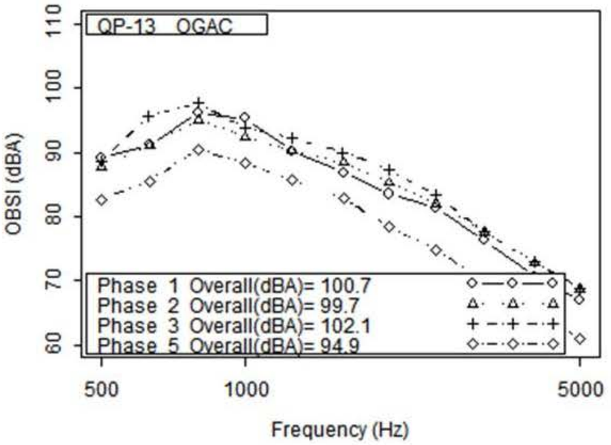

QP-08 RAC-O
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.2
Phase 3 Overall(dBA)= 99.4
Phase 4 Overall(dBA)= 98.5
Phase 5 Overall(dBA)= 99.6
Phase 6 Overall(dBA)= 101.8
500
1000
5000
Frequency (Hz)

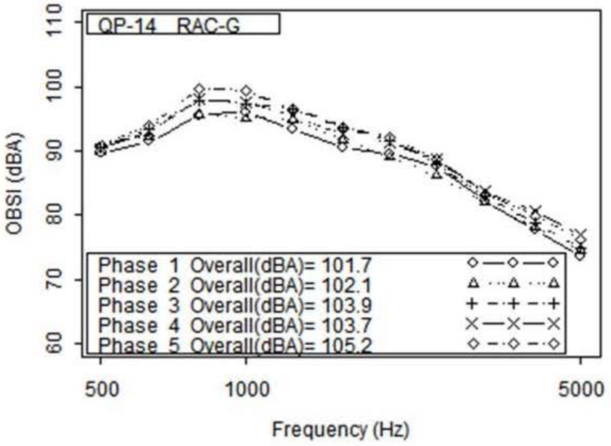

QP-09 DGAC
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 102.6
Phase 3 Overall(dBA)= 103.8
Phase 4 Overall(dBA)= 103.4
Phase 5 Overall(dBA)= 104
Phase 6 Overall(dBA)= 104
500
1000
5000
Frequency (Hz)

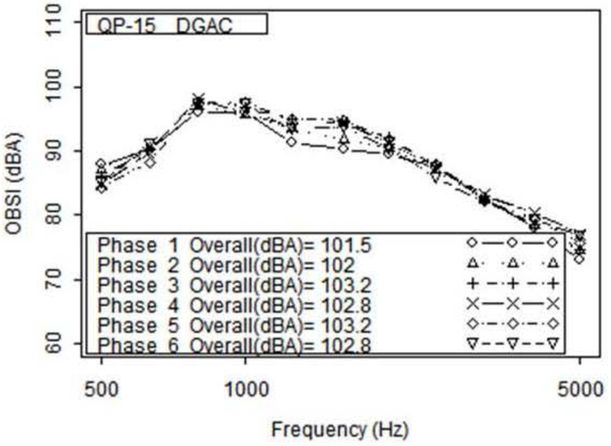

QP-10 RAC-G
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 102.3
500
1000
5000
Frequency (Hz)

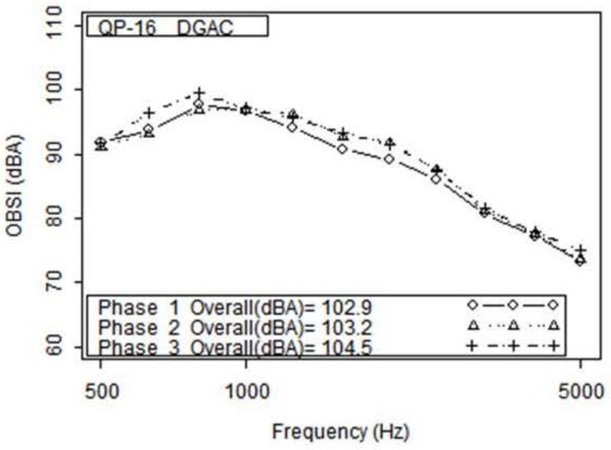

QP-11 DGAC
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 102.5
500
1000
5000
Frequency (Hz)

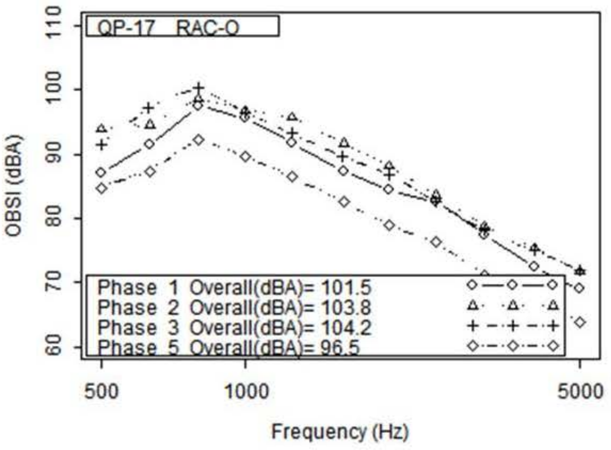

QP-12 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 99.3
Phase 3 Overall(dBA)= 99.3
Phase 4 Overall(dBA)= 100.9
Phase 5 Overall(dBA)= 101.8

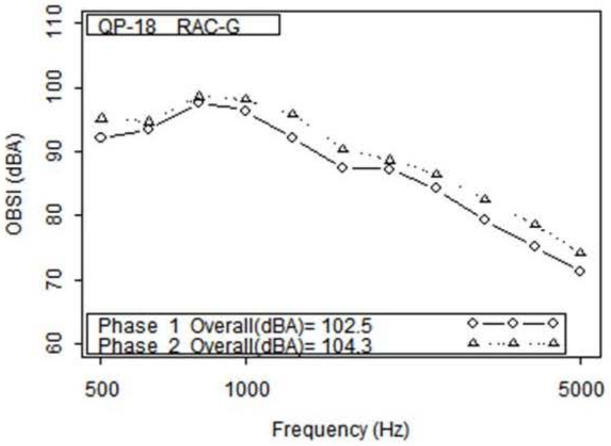

QP-13 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 102.1
Phase 5 Overall(dBA)= 94.9

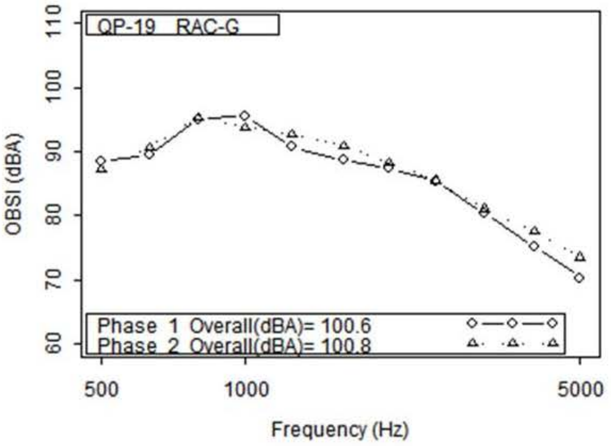

QP-14 RAC-G
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.1
Phase 3 Overall(dBA)= 103.9
Phase 4 Overall(dBA)= 103.7
Phase 5 Overall(dBA)= 105.2

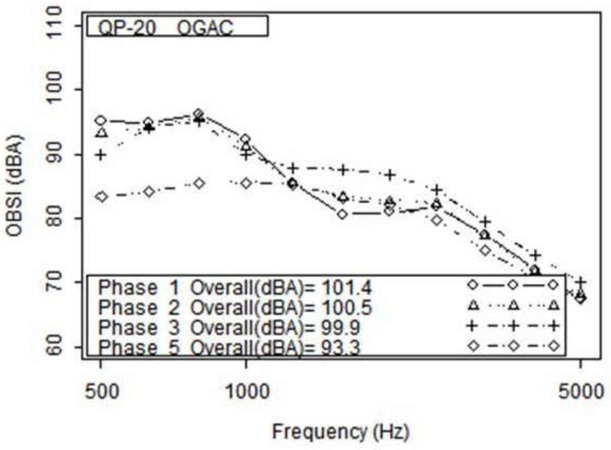

QP-15 DGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 102
Phase 3 Overall(dBA)= 103.2
Phase 4 Overall(dBA)= 102.8
Phase 5 Overall(dBA)= 103.2
Phase 6 Overall(dBA)= 102.8

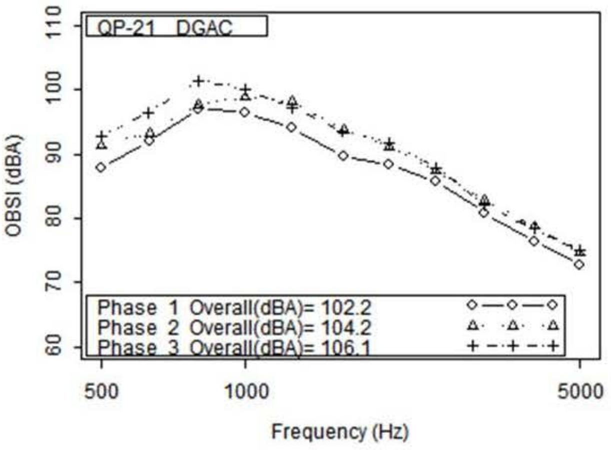

QP-16 DGAC
Phase 1 Overall(dBA)= 102.9
Phase 2 Overall(dBA)= 103.2
Phase 3 Overall(dBA)= 104.5
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)

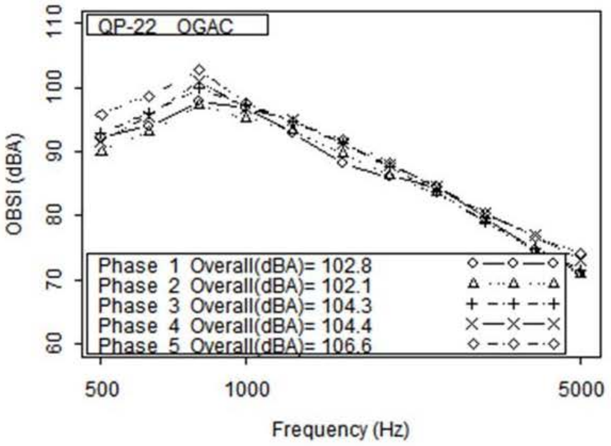

QP-17 RAC-O
Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 103.8
Phase 3 Overall(dBA)= 104.2
Phase 5 Overall(dBA)= 96.5
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)

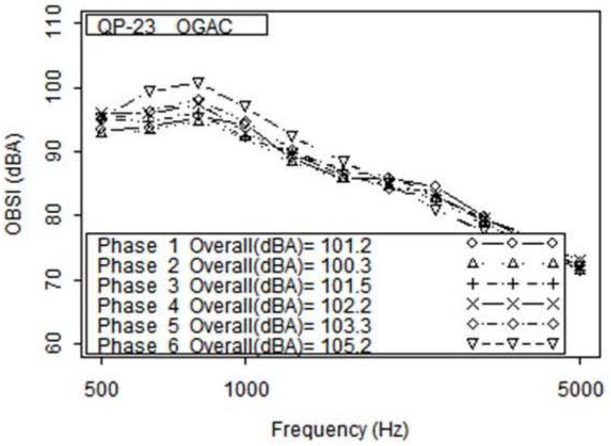

QP-18 RAC-G
Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 104.3
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)

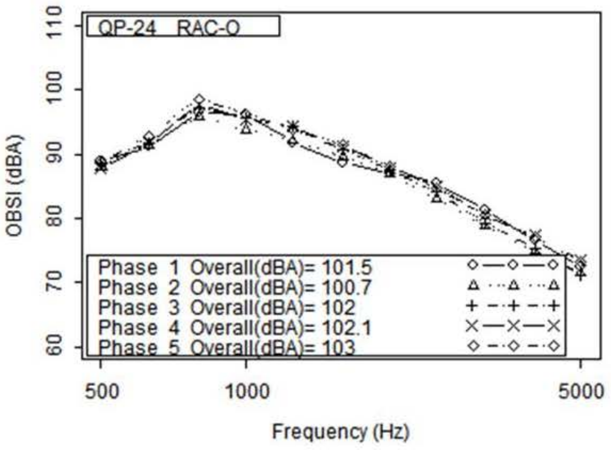

QP-19 RAC-G
Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 100.8
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)

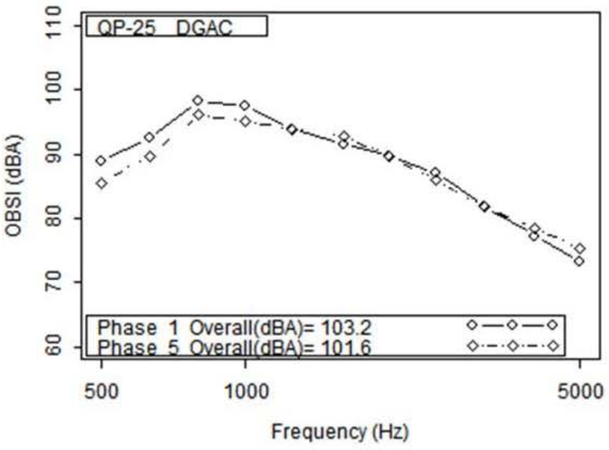

QP-20 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 99.9
Phase 5 Overall(dBA)= 93.3

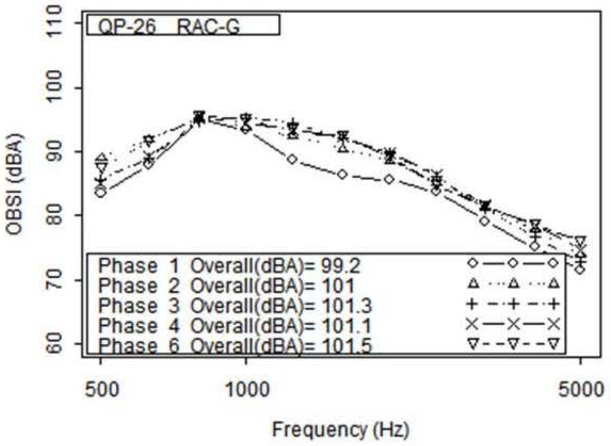

QP-21 DGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102.2
Phase 2 Overall(dBA)= 104.2
Phase 3 Overall(dBA)= 106.1

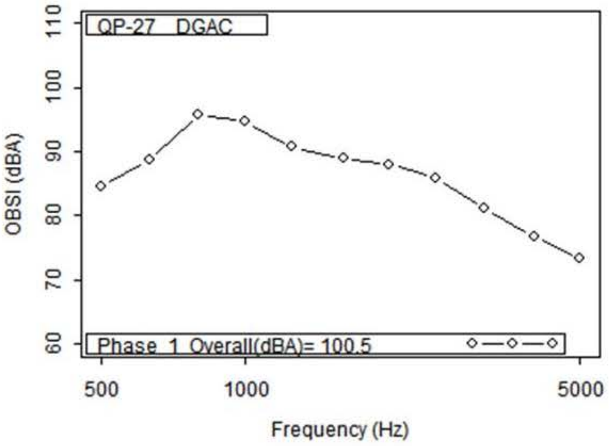

QP-22 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 102.1
Phase 3 Overall(dBA)= 104.3
Phase 4 Overall(dBA)= 104.4
Phase 5 Overall(dBA)= 106.6

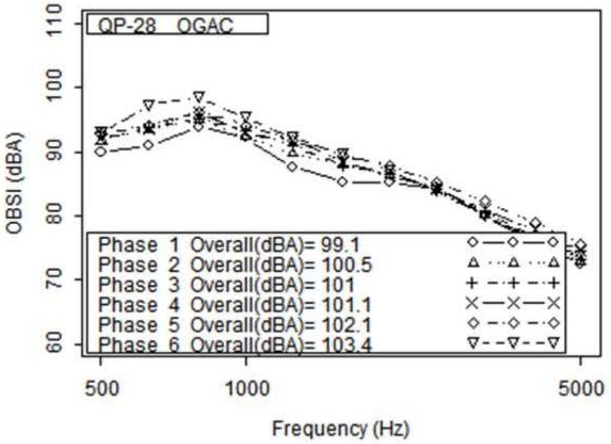

QP-23 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 101.5
Phase 4 Overall(dBA)= 102.2
Phase 5 Overall(dBA)= 103.3
Phase 6 Overall(dBA)= 105.2

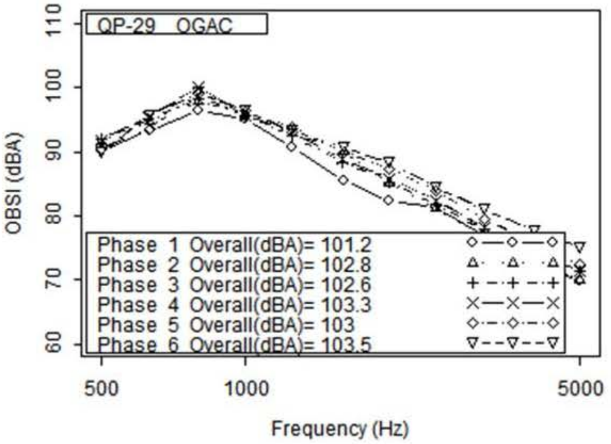

QP-24 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 100.7
Phase 3 Overall(dBA)= 102
Phase 4 Overall(dBA)= 102.1
Phase 5 Overall(dBA)= 103

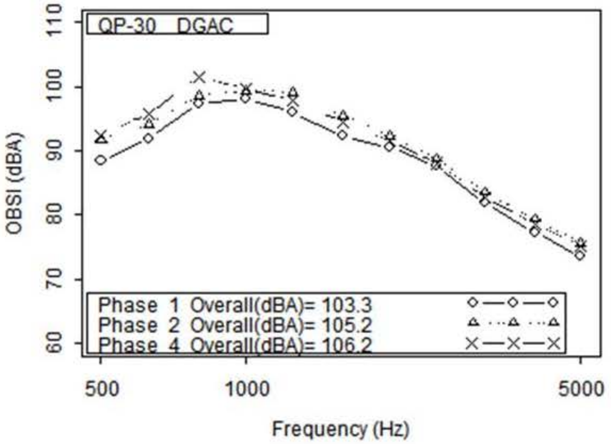

QP-25 DGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 103.2
Phase 5 Overall(dBA)= 101.6

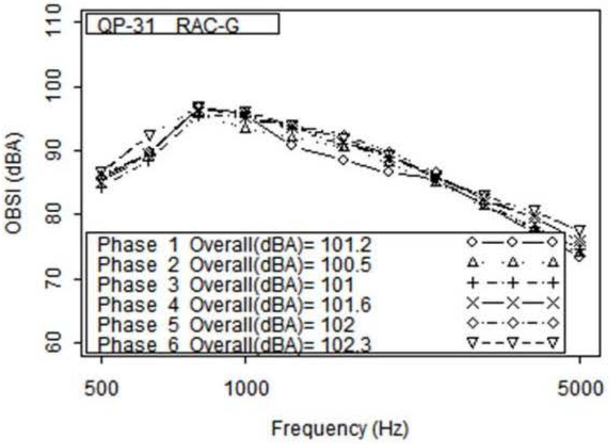

QP-26 RAC-G
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 99.2
Phase 2 Overall(dBA)= 101
Phase 3 Overall(dBA)= 101.3
Phase 4 Overall(dBA)= 101.1
Phase 6 Overall(dBA)= 101.5

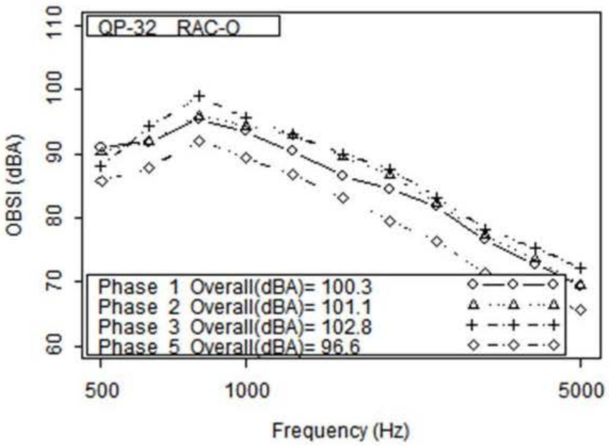

QP-27 DGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.5

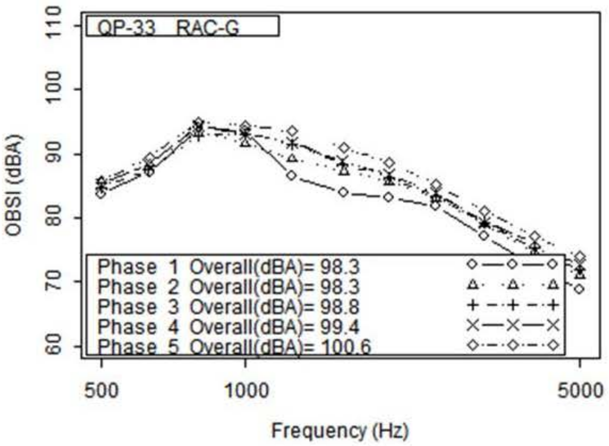

QP-28 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 99.1
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101
Phase 4 Overall(dBA)= 101.1
Phase 5 Overall(dBA)= 102.1
Phase 6 Overall(dBA)= 103.4

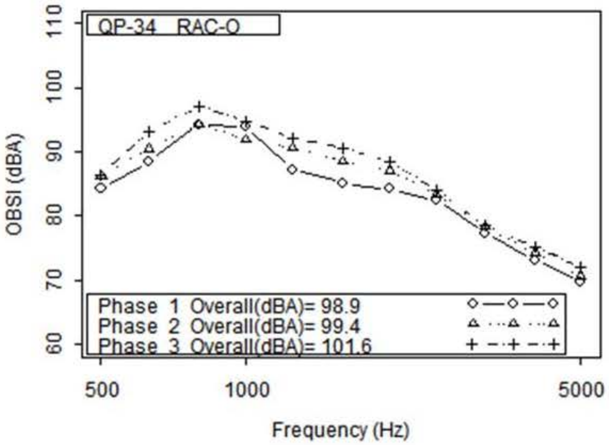

QP-29 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 102.8
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 103.3
Phase 5 Overall(dBA)= 103
Phase 6 Overall(dBA)= 103.5

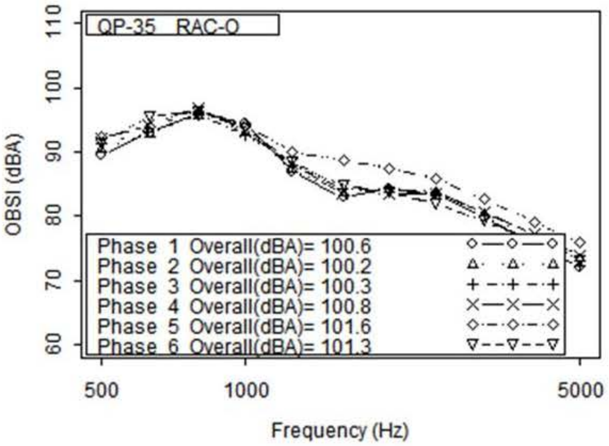

QP-30 DGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 103.3
Phase 2 Overall(dBA)= 105.2
Phase 4 Overall(dBA)= 106.2

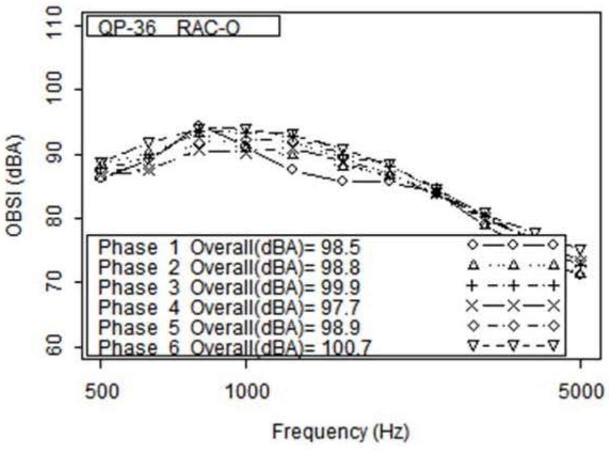

QP-31 RAC-G
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101
Phase 4 Overall(dBA)= 101.6
Phase 5 Overall(dBA)= 102
Phase 6 Overall(dBA)= 102.3

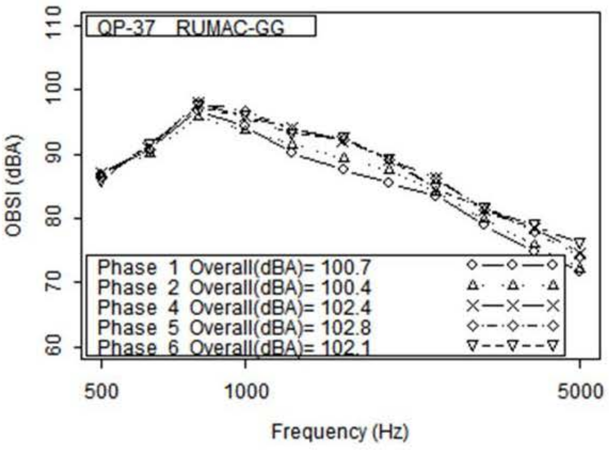

QP-32 RAC-O
OBSI (dBA)
110
100
90
80
70
60
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 102.8
Phase 5 Overall(dBA)= 96.6

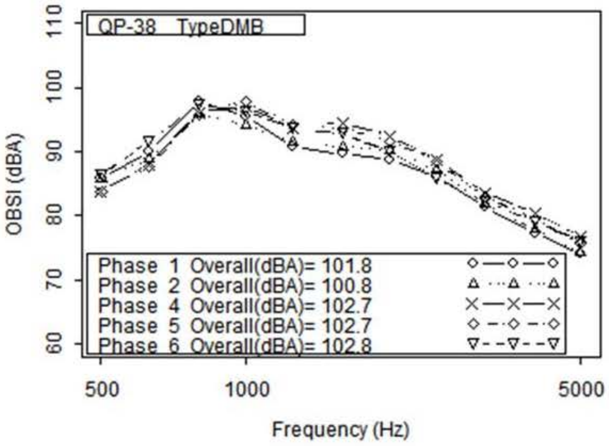

QP-33 RAC-G
OBSI (dBA)
110
100
90
80
70
60
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 98.3
Phase 2 Overall(dBA)= 98.3
Phase 3 Overall(dBA)= 98.8
Phase 4 Overall(dBA)= 99.4
Phase 5 Overall(dBA)= 100.6

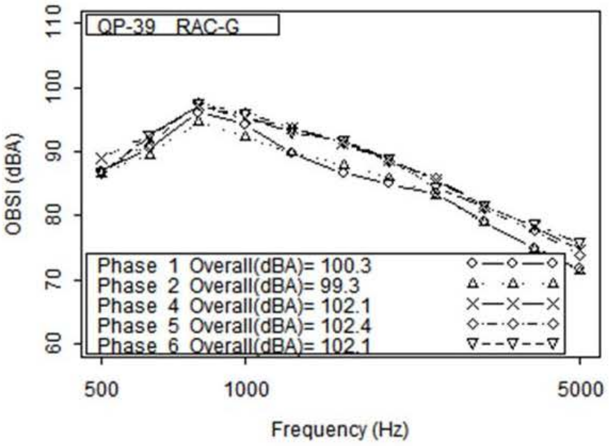

QP-34 RAC-O
OBSI (dBA)
110
100
90
80
70
60
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 98.9
Phase 2 Overall(dBA)= 99.4
Phase 3 Overall(dBA)= 101.6

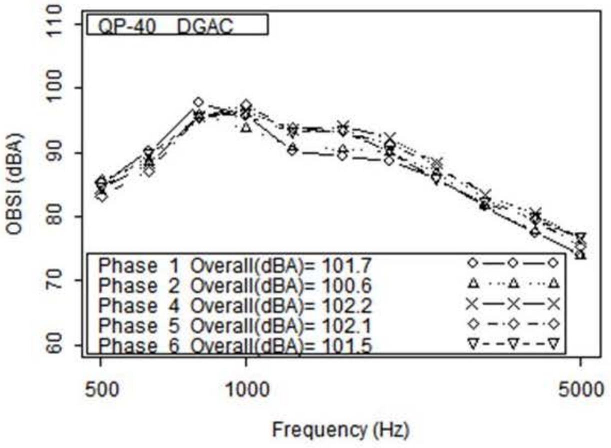

QP-35 RAC-O
OBSI (dBA)
110
100
90
80
70
60
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 100.2
Phase 3 Overall(dBA)= 100.3
Phase 4 Overall(dBA)= 100.8
Phase 5 Overall(dBA)= 101.6
Phase 6 Overall(dBA)= 101.3

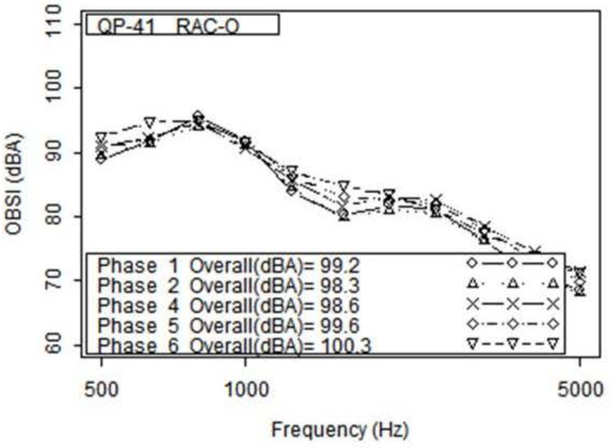

QP-36 RAC-O
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.8
Phase 3 Overall(dBA)= 99.9
Phase 4 Overall(dBA)= 97.7
Phase 5 Overall(dBA)= 98.9
Phase 6 Overall(dBA)= 100.7

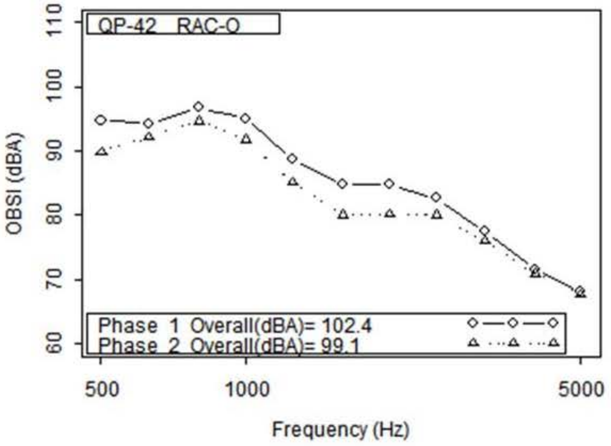

QP-37 RUMAC-GG
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 100.4
Phase 4 Overall(dBA)= 102.4
Phase 5 Overall(dBA)= 102.8
Phase 6 Overall(dBA)= 102.1

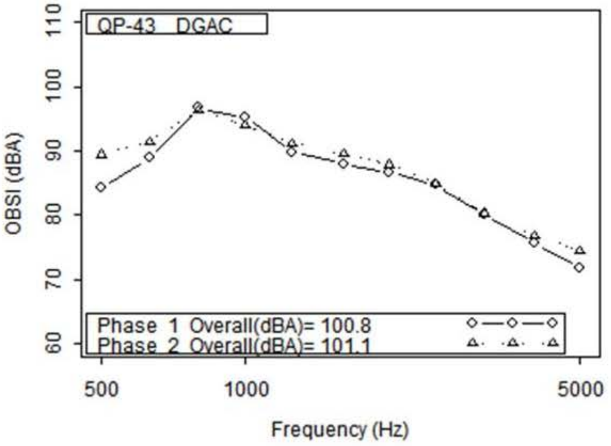

QP-38 TypeDMB
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 100.8
Phase 4 Overall(dBA)= 102.7
Phase 5 Overall(dBA)= 102.7
Phase 6 Overall(dBA)= 102.8

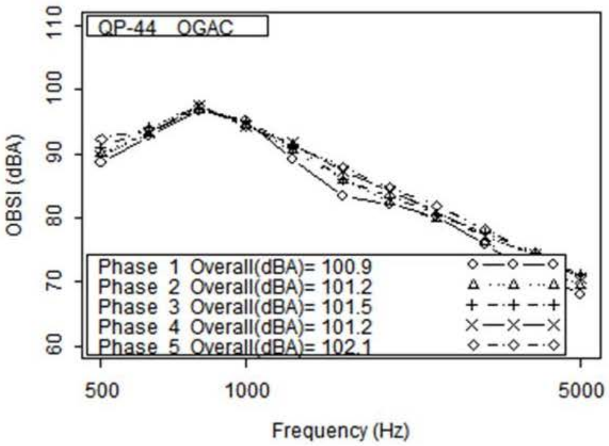

QP-39 RAC-G
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 99.3
Phase 4 Overall(dBA)= 102.1
Phase 5 Overall(dBA)= 102.4
Phase 6 Overall(dBA)= 102.1

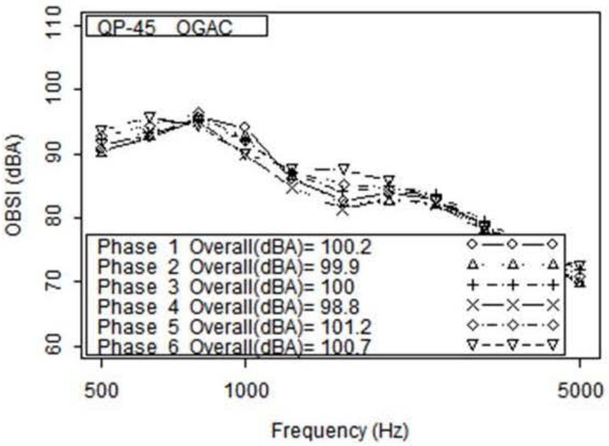

QP-40 DGAC
OBSI (dBA)
60
70
80
90
100
110
Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 100.6
Phase 4 Overall(dBA)= 102.2
Phase 5 Overall(dBA)= 102.1
Phase 6 Overall(dBA)= 101.5
500
1000
5000
Frequency (Hz)

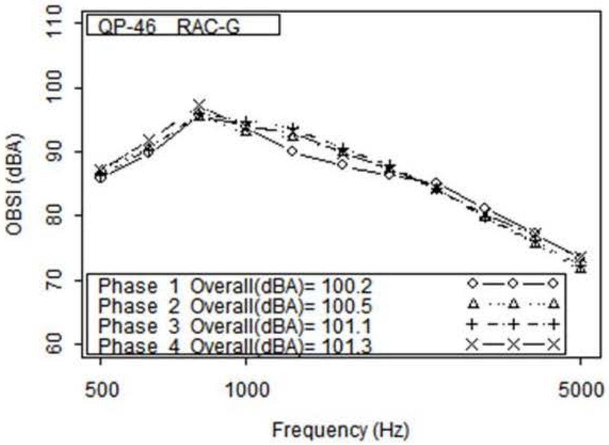

QP-41 RAC-O
OBSI (dBA)
60
70
80
90
100
110
Phase 1 Overall(dBA)= 99.2
Phase 2 Overall(dBA)= 98.3
Phase 4 Overall(dBA)= 98.6
Phase 5 Overall(dBA)= 99.6
Phase 6 Overall(dBA)= 100.3
500
1000
5000
Frequency (Hz)

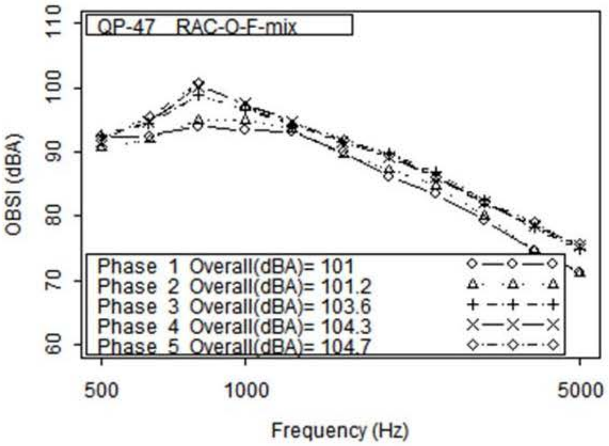

QP-42 RAC-O
OBSI (dBA)
60
70
80
90
100
110
Phase 1 Overall(dBA)= 102.4
Phase 2 Overall(dBA)= 99.1
500
1000
5000
Frequency (Hz)

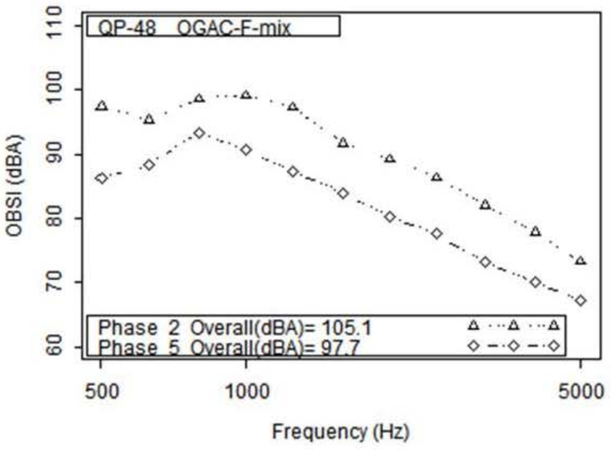

QP-43 DGAC
OBSI (dBA)
60
70
80
90
100
110
Phase 1 Overall(dBA)= 100.8
Phase 2 Overall(dBA)= 101.1
500
1000
5000
Frequency (Hz)

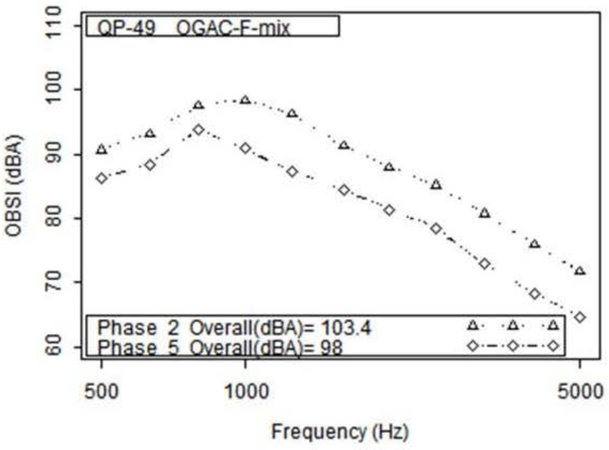

QP-44 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.9
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 101.5
Phase 4 Overall(dBA)= 101.2
Phase 5 Overall(dBA)= 102.1

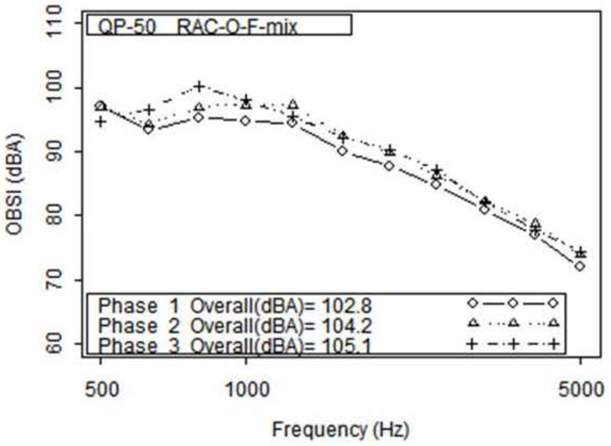

QP-45 OGAC
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 99.9
Phase 3 Overall(dBA)= 100
Phase 4 Overall(dBA)= 98.8
Phase 5 Overall(dBA)= 101.2
Phase 6 Overall(dBA)= 100.7

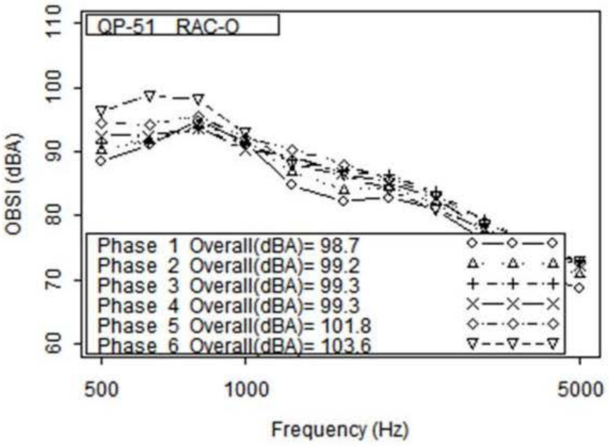

QP-46 RAC-G
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101.1
Phase 4 Overall(dBA)= 101.3

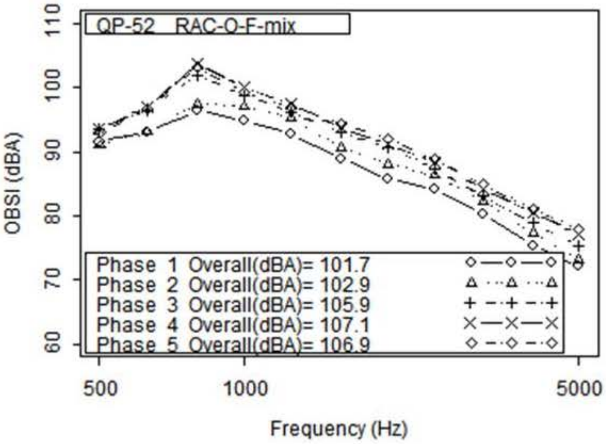

QP-47 RAC-O-F-mix
OBSI (dBA)
60
70
80
90
100
110
500
1000
5000
Frequency (Hz)
Phase 1 Overall(dBA)= 101
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 103.6
Phase 4 Overall(dBA)= 104.3
Phase 5 Overall(dBA)= 104.7


QP-48 OGAC-F-mix
OBSI (dBA)
60
70
80
90
100
110
Phase 2 Overall(dBA)= 105.1
Phase 5 Overall(dBA)= 97.7
500
1000
5000
Frequency (Hz)


QP-49 OGAC-F-mix
OBSI (dBA)
60
70
80
90
100
110
Phase 2 Overall(dBA)= 103.4
Phase 5 Overall(dBA)= 98
500
1000
5000
Frequency (Hz)


QP-50 RAC-O-F-mix
OBSI (dBA)
60
70
80
90
100
110
Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 104.2
Phase 3 Overall(dBA)= 105.1
500
1000
5000
Frequency (Hz)


QP-51 RAC-O
OBSI (dBA)
60
70
80
90
100
110
Phase 1 Overall(dBA)= 98.7
Phase 2 Overall(dBA)= 99.2
Phase 3 Overall(dBA)= 99.3
Phase 4 Overall(dBA)= 99.3
Phase 5 Overall(dBA)= 101.8
Phase 6 Overall(dBA)= 103.6
500
1000
5000
Frequency (Hz)


QP-52 RAC-O-F-mix
OBSI (dBA)
110
100
90
80
70
60
Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.9
Phase 3 Overall(dBA)= 105.9
Phase 4 Overall(dBA)= 107.1
Phase 5 Overall(dBA)= 106.9
500
1000
5000
Frequency (Hz)

Appendix B.6: Actual Values Predicted by Regression Models for Chapter 6

Table B.19: Predicted Lifetime of Different Asphalt Mix Types with Respect to Roughness

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	15	17	15	18
	Moderate Rainfall/ Low Temperature	9	11	8	16
	High Rainfall/ Moderate Temperature	8	11	11	16
	Moderate Rainfall/ Moderate Temperature	9	12	10	16
Low Traffic (TI=9)	Low Rainfall/ High Temperature	12	17	15	18
	Moderate Rainfall/ Low Temperature	10	12	11	16
	High Rainfall/ Moderate Temperature	11	12	10	15
	Moderate Rainfall/ Moderate Temperature	10	12	11	15

Table B.20: Predicted Lifetime of Different Asphalt Mix Types with Respect to Noise from First Model

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	-	9	5	15
	Moderate Rainfall/ Low Temperature	-	9	8	14
	High Rainfall/ Moderate Temperature	-	8	6	14
	Moderate Rainfall/ Moderate Temperature	-	9	6	13
Low Traffic (TI=9)	Low Rainfall/ High Temperature	-	9	6	14
	Moderate Rainfall/ Low Temperature	-	10	9	13
	High Rainfall/ Moderate Temperature	-	11	7	13
	Moderate Rainfall/ Moderate Temperature	-	10	7	14