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Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.29:
Five-Year Field Evaluation of Tire/Pavement Noise, IRI and Macrotexture of Flexible Pavements

PREPARED FOR:

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Division of Research and Innovation
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DOCUMENT RETRIEVAL PAGE			**Research Report:** UCPRC-RR-2012-04
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Abstract: The work presented in this report is summary of a series of research projects, whose central purpose is to support the Caltrans Quieter Pavement Research Program, which has as its goals and objectives the identification of quieter, smoother, safer, and more durable pavement surfaces. The research has been carried out as Partnered Pavement Research Center Strategic Plan Elements (SPE) 4.16, 4.19, 4.27, and 4.29.

In the study documented in this report, field data regarding tire/pavement noise, ride quality, and macrotexture were collected over five consecutive years from pavements in California placed with open-graded and other asphaltic mixes. The five-year data were analyzed to evaluate the ride quality and effectiveness of open-graded mixes in reducing noise compared to other asphalt surfaces, including dense- and gap-graded mixes, and to evaluate the pavement characteristics that affect tire/pavement noise. The analysis in this report is a supplement and update to four previous studies on the first four years of data collected, which are detailed in four separate reports.

Models have been updated, with some changes in the use of condition survey variables. Conclusions are made regarding the performance of open-graded mixes and rubberized mixes (RAC-G), comparisons are made with dense-graded mixes (DGAC), and the effects of variables affecting tire/pavement noise are examined.

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

Proposals for implementation: No proposals for implementation are presented in this report.

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 Caltrans Department of Research and Innovation.
- *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 Caltrans Department of Research and Innovation.
- 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 Caltrans Department of Research and Innovation.
- 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 for Caltrans by the Danish Road Institute, Road Directorate and University of California Pavement Research Center.
- 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 Caltrans Department of Research and Innovation.
- Work Plan for Project 4.27, “Fourth Year of Noise and Smoothness Monitoring of Flexible Pavements” (UCPRC-WP-2008-16). Work Plan prepared by UCPRC for the Caltrans Department of Research and Innovation.
- 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 Caltrans Department of Research and Innovation.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

The research presented in this report is part of the California Department of Transportation (Caltrans) Quieter Pavement Research (QPR) Work Plan, whose central purpose is to support the Caltrans Quieter Pavement Research Program. This program's goals and objectives are to identify quieter, safer, and more durable asphalt pavement surfaces.

The purpose of the project presented in this report, which is part of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.29, is to perform a fifth year of measurement of the tire/pavement noise, ride quality, and macrotexture of 74 flexible pavement sections, and to provide an updated preliminary table of estimated design lives for different treatments with respect to the variables measured.

PPRC SPE 4.29 has the following objectives:

1. To perform a fifth year of collection of OBSI and IRI data from existing flexible pavement test sections.
2. To upgrade the noise car used in collecting data for the study.
3. To collect additional information on existing test sections to help explain changes observed in OBSI and IRI. This additional information consists of surface macrotexture measurements.
4. To combine the new data with the existing fourth year of performance measurement in order to determine rates of change for noise and smoothness of asphalt-surfaced sections.
5. To report updated trends for noise (OBSI) and smoothness (IRI), and to model them where applicable.

This report documents the work completed for all these objectives.

EXECUTIVE SUMMARY

Background and Purpose

The California Department of Transportation (Caltrans) employs a variety of strategies and materials for maintaining and rehabilitating the state's highways pavements. Since the smoothness and quietness of pavements are gaining attention and importance as they affect quality of life issues for highway users and neighboring residents, Caltrans has sought to identify the lives of those strategies and materials, as well as those of new candidates, that can maintain roadway smoothness and quietness for the longest time. To accomplish this, Caltrans established the Quieter Pavement Research (QPR) Program.

The intention behind the Caltrans QPR program is to examine the impact of quieter pavements on traffic noise levels and to establish which pavement 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 Caltrans QPR program will be used to develop quieter-pavement 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 QPR Work Plan includes research on both asphalt and concrete pavement surfaces. For the flexible (asphalt-surfaced) pavement part of the QPR study, Caltrans previously identified a need for research into the acoustics, friction, and performance of asphalt pavement surfaces, and in November 2004 initiated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 as a response. Among its other objectives, PPRC SPE 4.16 developed preliminary performance estimates for current Caltrans asphalt surfaces—including DGAC, OGAC, RAC-G, and RAC-O as part of a factorial experiment—and a number of experimental asphalt surfaces with respect to tire/pavement noise, permeability, macrotexture, microtexture, smoothness, and surface distress development. *(Note*: The technical names for these mixes have changed in the new Section 39 of the Caltrans Standard Specifications. However, in this report the names in use at the start of PPRC SPE 4.16 have been maintained to ensure consistency among all the reports and technical memoranda generated by the quieter pavement studies.) The results of PPRC SPE 4.16 warranted a continuation of field monitoring of tire/pavement noise and other surface properties on the same asphalt pavements. The effort to complete PPRC SPE 4.16 was undertaken beginning in September 2007 as PPRC SPE 4.19, which was titled "Third Year Field Evaluation of Tire/Pavement Noise, IRI, Macrotexture, and Surface Condition of Flexible Pavements. The study was further continued in 2008/2009 in PPRC SPE 4.27, titled "Fourth Year of Noise and Smoothness Monitoring of Flexible Pavements," and in 2009/2012 in PPRC SPE 4.29, with the title "Fifth Year of Noise and Smoothness

Monitoring of Flexible Pavements." This report summarizes the results from the fifth-year study, and utilizes all the data collected over the five-year study period.

Objectives

The purpose of this most recent part of PPRC SPE 4.29 is to perform a fifth year of measurements of tire/pavement noise, ride quality, and macrotexture on up to 74 flexible pavement sections in order to improve performance estimates for identifying the more durable, smoother, and quieter asphalt pavement surface types.

Following are the objectives of PPRC SPE 4.29:

1. To perform a fifth year of collection of OBSI and IRI data from existing flexible pavement test sections.
2. To upgrade the noise car used in collecting data for the study.
3. To collect additional information on existing test sections to help explain changes observed in OBSI and IRI. This additional information consists of surface macrotexture measurements.
4. To combine the new data with the existing four-year performance history in order to determine rates of change for the noise and smoothness of asphalt-surfaced sections.
5. To report updated trends for noise (OBSI) and smoothness (IRI), and to model them where applicable.

Scope of the Report

This report documents the work completed for all of the objectives and is organized as follows:

- Chapter 1 presents the background of the study, its objectives, and the performance parameters for pavement surfaces.
- Chapter 2 provides a summary of the analysis results of the ride-quality data in terms of the International Roughness Index (IRI).
- Chapter 3 presents a summary of the analysis results of the macrotexture data in terms of Mean Profile Depth (MPD).
- Chapter 4 presents a summary of the analysis results of On-board Sound Intensity (OBSI) data.
- Chapter 5 presents a summary of the analysis results of the fifth-year data collected on the Environmental Sections (ES).
- Chapter 6 lists the conclusions from the analyses and includes preliminary recommendations.
- Appendices describe detailed analysis work and provide additional information in support of the conclusions in Chapter 6.

The data presented in this report includes the measurements collected in the fifth year, and is included in a relational database that will be delivered to Caltrans separately. Specific data in the database includes:

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

The analyses presented for each performance variable in Appendix 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

This study compares five consecutive 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). As noted, since the start of the study, these materials have been renamed as OGAC, rubberized hot-mix asphalt open graded (RHMA-O), rubberized hot-mix asphalt gap-graded (RHMA-G) and hot-mix asphalt (HMA). The original names have been used throughout this report. Categories of data include tire/pavement noise, ride quality, and macrotexture. The five years of data were analyzed in this report with the following 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 equations 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

It should be noted that that in the fifth year report the models that were developed in the fourth year report were updated with fifth-year data, and previous surface condition variables (rutting, fatigue cracking) were removed from the models because of difficulties with the year-to-year consistency of visual condition surveys. MPD, however, was introduced into individual models as an indication of raveling. As with the fourth-year report, two types of models were developed. In the first type, data for all the mixes were pooled and the models were developed from them. In the second type, the models were developed for individual mixes using data from all five years.

Performance of Open-Graded Mixes

As was found in the fourth-year report, newly paved overlays, the OGAC, RAC-G, and RAC-O open-graded mixes had lower tire/pavement noise than DGAC mixes by average levels of 3.7 dB(A), 1.6 dB(A), and 3.0 dB(A), respectively. For comparison, the average tire/pavement noise level was approximately 101.3 dB(A) for newly paved DGAC overlays.

After the pavements were exposed to traffic, this noise benefit generally diminished slightly after about seven to nine years for OGAC. RAC-O is quieter than OGAC and keeps a noise-reduction benefit longer than OGAC. For pavements older than nine years, although no RAC-O pavement was found to provide a noise reduction benefit of 3 dB(A) or more, there was still a noise reduction benefit observed for RAC-O pavements compared with DGAC of the same age with 50 percent of RAC-O pavements 2 dB(A) quieter than DGAC pavements.

Newly paved open-graded, OGAC and RAC-O overlays generally had higher low-frequency noise and lower high-frequency noise than dense-graded mixes. In the first five years after the OGAC mixes were exposed to traffic, high-frequency noise increased with age due to the reduction of surface permeability and air-void content under traffic. Low-frequency noise increased with age, likely due to the increase in surface distresses, primarily raveling. This effect was less pronounced for RAC-O pavements. For the open-graded mixes (OGAC and RAC-O) between one and four years old, a large increase in high frequency noise between 1,000 Hz and 2,500 Hz was observed after five years.

MPD was initially lower for RAC-O than for OGAC and increased more slowly on RAC-O pavements than on OGAC pavements. IRI had lower initial values and increased more slowly on RAC-O pavements than on OGAC pavements.

Performance of RAC-G Mixes

Newly paved RAC-G mixes were quieter than an average newly paved DGAC mix by about 1.8 dB(A). 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. Old RAC-G pavements had a higher rate of increase in overall noise intensity of 0.56 dB(A) per year compared to DGAC pavements which had a noise increase rate of 0.38 dB(A) per year. Among newly paved overlays, 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. For RAC-G pavements older than three years, noise of all frequencies increased with age but more on the low-frequency side of the frequency spectrum.

The IRI values on newly paved RAC-G mixes were higher those on DGAC mixes. The rate of increase in IRI for RAC-G mixes was smaller than for DGAC mixes. Therefore, older RAC-G mixes had lower IRI values compared to their DGAC counterparts. The MPD value on newly paved RAC-G mixes was higher than on DGAC mixes. The rate of increase in MPD was similar for both RAC-G and DGAC.

Performance of Environmental Sections

During the fifth year of noise study, the noise, ride quality, and surface macrotexture of twenty-three environmental sections were collected and following conclusions were drawn:

- Based on the Fresno 33 sections, RAC-G and Type G-MB mixes generally exhibited the highest and lowest MPD values, respectively. RAC-G and RUMAC-GG exhibited higher IRI values than Type G-MB, Type D-MB, and DGAC mixes. There was no indication of the effect of layer thickness on the measured IRI and MPD. Type G-MB 45-mm thick overlays exhibited the lowest sound intensity with a value of 102.7 dB(A) in the fifth year of data collection. None of these mixes provided any noise reduction compared to the DGAC mix after three years.
- Between the two sections with thin RAC-O overlays on concrete pavement, the San Mateo 280 section performed better after five years than the Sacramento 5 sections in terms of both noise and roughness, possibly due to its greater thickness and lower truck traffic. The RAC-O pavement placed on the Sacramento 5 northbound exhibited a major increase in the IRI and noise in the fifth year of data collection.
- From the LA 138 test sections, which include sections with DGAC, OGAC, RAC-O, and BWC mixes, it was found that RAC-O mixes have the highest IRI values, and OGAC mixes have the lowest noise levels among all the mix types over the five survey years.
- The EU-GG mix on LA 19 performed well in terms of providing a noise-reduction benefit compared with the statewide data for DGAC. The year-to-year increase in IRI for this mix was not significant.
- The Yolo 80 section still provided good ride quality according to FHWA guidelines but lost its noise-reducing capabilities, compared with statewide data for DGAC.

- Almost all BWC sections provide good ride quality for interstate pavements. Polymer-modified open-graded BWC mixes rapidly lost their noise-reduction advantage, whereas polymer-modified gap graded BWC mixes maintained their noise-reduction advantage for a longer period.

Variables Affecting Tire/Pavement Noise

The findings from this fifth year of the study regarding variables that affect tire/pavement noise are generally in agreement with the significant factors found in previous reports. That is, tire/pavement noise is greatly influenced by surface mix type and mix properties, age, traffic volume, and the presence of distresses, indicated by MPD as a substitute for raveling in this report. 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 all mix types (DGAC, RAC-G, OGAC, and RAC-O), neither the aggregate gradation variable (fineness modulus) nor NMAS seemed to significantly affect tire/pavement noise. 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, since greater MPD is typically associated with higher air-void content.

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
in.	inches	25.4	millimeters	mm
Ft	feet	0.305	meters	m
AREA				
in.^{2}	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	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	poundforce	4.45	newtons	N
lbf/in.^{2}	poundforce/square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm	millimeters	0.039	inches	in.
m	meters	3.28	feet	ft
AREA				
mm^2	square millimeters	0.0016	square inches	in.^{2}
m^2	square meters	10.764	square feet	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	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce/square inch	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 of concern are *pavement smoothness* and *quietness,* as these affect the quality of life of both highway users and neighboring residents. 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 new candidates. In order to accomplish this identification, 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 research presented in this report is part of one of these studies and is an element of the Caltrans Quieter Pavements Research (QPR) Work Plan.

The Caltrans QPR Work Plan includes research on both asphalt and concrete pavement surfaces. For the flexible (asphalt-surfaced) pavement part of the QPR study, Caltrans previously identified a need for research into the acoustics, friction, and distress performance of asphalt pavement surfaces, and in November 2004 it initiated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 as a response. 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]

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, and laboratory testing of field cores. The results of the first two years of data collection, modeling, and performance predictions, as summarized in References *(1)* and *(2),* warranted a continuation of field monitoring of tire/pavement noise and other surface properties on the same asphalt pavements included in the PPRC SPE 4.16 study. Therefore, PPRC SPE 4.19, titled "Third Year Field Evaluation of Tire/Pavement Noise, IRI, Macrotexture, and Surface Condition of Flexible Pavements," was initiated in September 2007. Results from PPRC SPE 4.19, which included performance estimates from the third year of measurements on most of the pavement sections included in the PPRC SPE 4.16 project and were combined with data from the first two years of data collection, were summarized in Reference *(3)*. The QPR study was further continued with measurements taken in 2008 and 2009 under PPRC SPE 4.27, and resulted in the research report titled "Fourth Year of Noise and Smoothness Monitoring of Flexible Pavements." A continuation of the study was then carried out for a fifth year under PPRC SPE 4.29, titled "Fifth Year of Noise and Smoothness Monitoring of Flexible Pavements," in 2009/2010. This current report summarizes the results from the fifth-year study, combining the data from all five years of measurements.

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, and the remaining planned data collection for both studies.

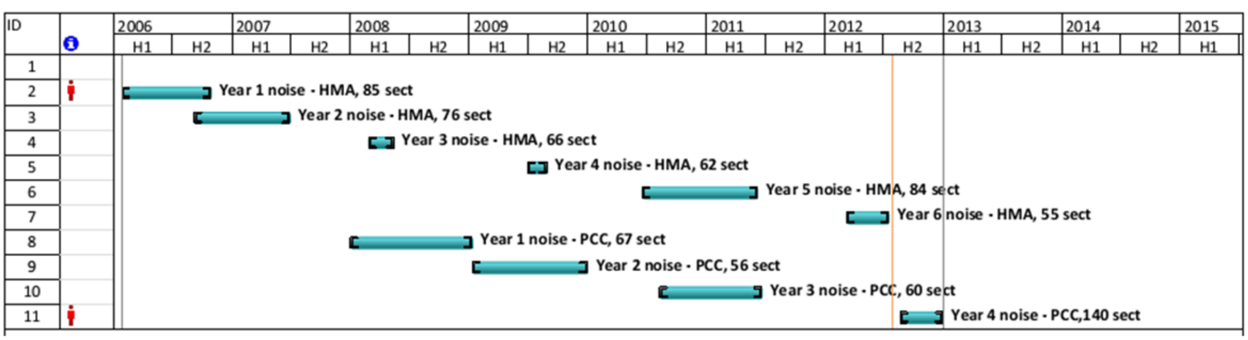

Figure 1.1: Timeline of completed and planned data collection periods for asphalt and concrete pavement noise studies.

[1] The technical names for these mixes changed in the new 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).

1.2 Project Purpose and Objectives

The purpose of PPRC SPE 4.29 was to perform a fifth year of measurement of tire/pavement noise, ride quality, and macrotexture of up to 74 flexible pavement sections in order to improve performance estimates so that smoother and quieter pavement types can be identified.

PPRC SPE 4.29 had these objectives:

- To perform a fifth year of collection of OBSI and IRI data from existing flexible pavement test sections.
- To collect additional information on existing test sections in order to help explain changes observed in OBSI and IRI. This additional information consists of surface macrotexture measurement data.
- To combine the new data with the existing four-year performance history in order to determine rates of change for noise and smoothness of asphalt-surfaced sections.
- To report updated trends for noise (OBSI) and smoothness (IRI), and to model them where applicable.

1.3 Experiment Factorial for Fifth-Year Measurements

As noted earlier, as part of PPRC SPE 4.16, a factorial was developed for current Caltrans asphalt surfaces including DGAC, RAC-G, OGAC, and RAC-O.[2] That factorial included 51 sections, referred to as the *Quieter Pavement* (QP) sections, which were selected based on 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, several sections identified in other projects and 23 sections with new materials and their associated control sections—referred to as the *Environmental Sections* (ES)—were also tested. Appendix B.1: List of Test Sections Included in the Study shows specific test section information.

These sections have been tested for five years. The first two years of data included:

- Coring, condition survey, permeability, and friction (microtexture) tests performed within traffic closures;
- Profile and tire/pavement noise measurements performed at highway speeds with the instrumented noise car; and
- Mix property testing on cores performed in the laboratory.

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[2] See Footnote 1 on page 18 regarding terminology for pavement types used in this report.

The third-year data included condition surveys conducted from the highway shoulder, and profile and tire/pavement noise measurements performed at highway speeds. The fourth-year data included condition surveys performed from the shoulders, profile and tire/pavement noise measurements performed at highway speeds, and coring and permeability tests performed within traffic closures on 31 sections. The fifth-year data include profile and tire/pavement noise measurements performed at highway speeds.

Detailed descriptions of project testing methodologies, definitions, and background can be found in Reference *(2).* Most of the same data collection methodologies were continued in the fourth and fifth years. However, since the end of the second year Standard Reference Test Tires (SRTT) have been used for all noise measurements, replacing the Aquatred tires used for most of the first two years of measurement. All measurements from the first two years when the Aquatred tires were used were converted to equivalent noise levels measured with one specific SRTT tire using correction equations developed by the UCPRC at the end of the second year of measurement. Since that second year of measurement a new SRTT tire has been used for each year of measurement.

In addition, the Larson Davis noise data analyzer used in the first three years was changed to a Harmonie unit, and this introduced small changes on 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 developed and applied to the previous years' data to convert all measurements to the equivalents of measurements made by the Harmonie analyzer. All of the fifth year data were collected using the Harmonie unit, which made it unnecessary to apply corrections. Details of the correction equations used to convert data to the Harmonie analyzer and SRTT#1 are shown in Appendix B.2. Air density adjustments were applied to all data from all five years using correction equations documented in Reference *(2).*

A few pavement sections had maintenance or rehabilitation treatment by the third or fourth year and were dropped from the survey in the fifth year. Table 1.1 shows the number of sections surveyed for various performance measures in each of the five years. Tables B.1.1 and B.1.2 in Appendix B.1 detail which sections were included in each year of testing.

Table 1.1: Number of Sections with Valid Measurements in Five 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)
Tire/Pavement Noise (OBSI-California)*	76	71	65	62	65
Roughness (ASTM E1926)	78	71	69	67	65
Macrotexture (ASTM E1845)	77	72	60	67	65
Friction (ASTM E303)	83	73	0	0	0
Air-void Content/Aggregate Gradation**	83/83	73/73	0/0	27/0	0
Permeability (NCAT falling head)	78	73	0	31	0
Pavement distresses**	84	84	73	72	0

* 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 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. 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." A summary of conclusions and recommendations appears in Chapter 6. The details of data presentation, analysis, and modeling are given in the appendices.

2 SURFACE PROFILE RESULTS: IRI

International Roughness Index (IRI) was measured in all five years of data collection in order to evaluate the change in the surface roughness of asphalt pavements. The IRI measurements were collected in both the left and right wheelpaths. The average of the two wheelpath measurements—called mean roughness index (MRI)—along the whole length of each pavement section was used in the analysis.

Figure 2.1 shows the average IRI measured in five consecutive years for individual pavement sections for each of the four mix types in both the factorial experiment (Quieter Pavement, QP) and the Environmental Sections (ES): DGAC, OGAC, RAC-G, and RAC-O. The first data point for each section is shown at the age of the section when the first measurement was taken, with Year Zero defined as the year of construction of each section. The plots are shown with metric units (m/km) with a note showing conversion to U.S. standard units (in./mi). The study was initiated using metric units, and all data has continued to be recorded in metric units.

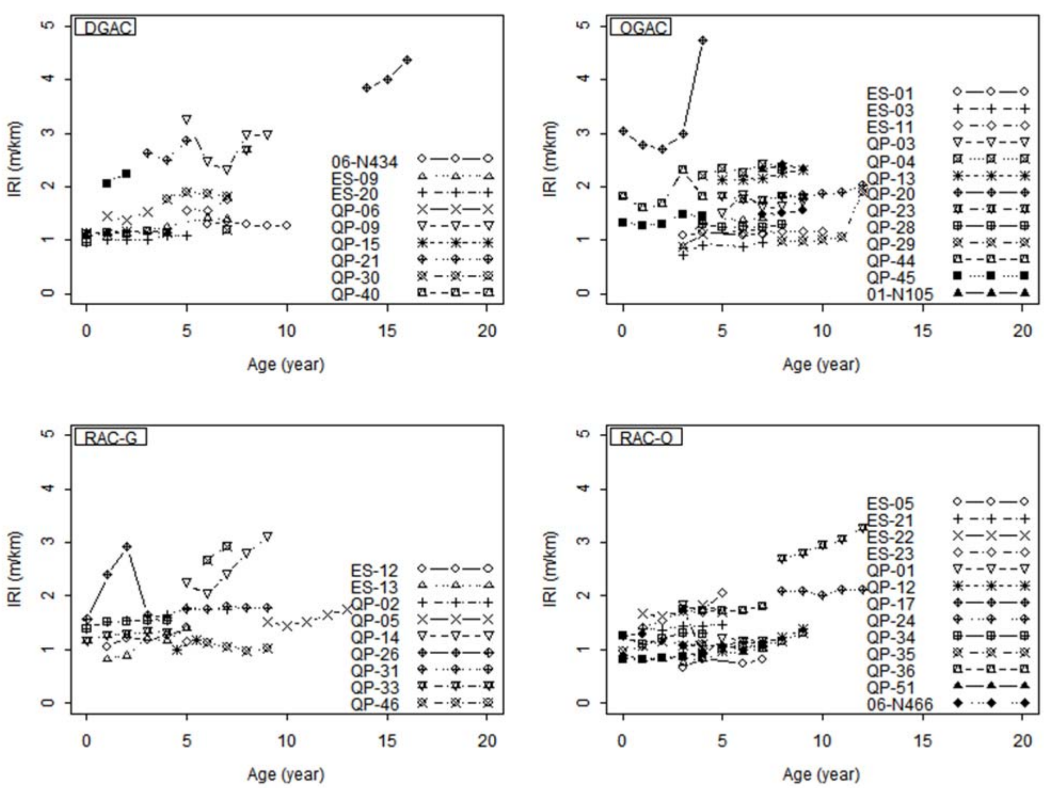

Figure 2.1: IRI trends over five years for each pavement section.
(Note: **1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi.)**

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 0.70 and 0.68, respectively, which shows some improvement in the DGAC and RAC-G models compared to the reported values of 0.65 in the fourth year report. The OGAC and RAC-O models have R^2 of 0.48 and 0.41, respectively. The R^2 for these two mixes has slightly improved compared to the fourth year report but the model still lacks accuracy in predicting a large portion of variation in the IRI in these two mixes.
2. It was found that in fifth year of data collection that all sections are smoother than the Caltrans Pavement Management System (PMS) IRI trigger criterion of 3.6 m/km (224 in./mi) except for old DGAC mix types. Many older DGAC pavements are rougher than the current PMS IRI trigger of 2.7 m/km (170 in./mi), and a few of the older sections with the other three mix types also exceed the new threshold.
3. Rubberized open-graded mixes have lower initial IRI values than nonrubberized open-graded mixes; rubberized gap-graded mixes have lower initial IRI values than nonrubberized dense-graded mixes. Inclusion of rubber results in a 19 percent reduction of initial IRI for RAC-G mixes compared with dense-graded mixes and about a 16 percent reduction in initial IRI for open-graded mixes.
4. The surface mix types RAC-G, RAC-O, and DGAC with ages less than one year all have lower initial IRI smaller than DGAC. The initial IRI values of all mixes older than one year do not exhibit a statistically significant difference. Monitoring over five years indicates that IRI increases with age on DGAC, RAC-G, and RAC-O pavements, but that age only has a statistically significant effect on the increase of IRI for RAC-O.
5. All pavements are smoother in high temperature regions than in low temperature regions but the effect of temperature is only significant for OGAC.
6. The IRI of DGAC, OGAC, RAC-G pavements increases with increasing MPD, and the increase is statistically significant for all mixes except RAC-O. The monitoring performed to date shows that traffic volume significantly affects IRI only on RAC-G pavements, with higher traffic volumes leading to higher IRI values.

3 SURFACE MACROTEXTURE RESULTS: MEAN PROFILE DEPTH

Macrotexture was measured by the UCPRC using a high-speed profilometer in the right wheelpath, and was reported 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 is analyzed in this report.

Figure 3.1 shows the average MPD measured over five consecutive years for individual pavement sections for four mix types: DGAC, OGAC, RAC-G, and RAC-O. It was expected that MPD would increase with pavement age, as pavements deteriorate with time.

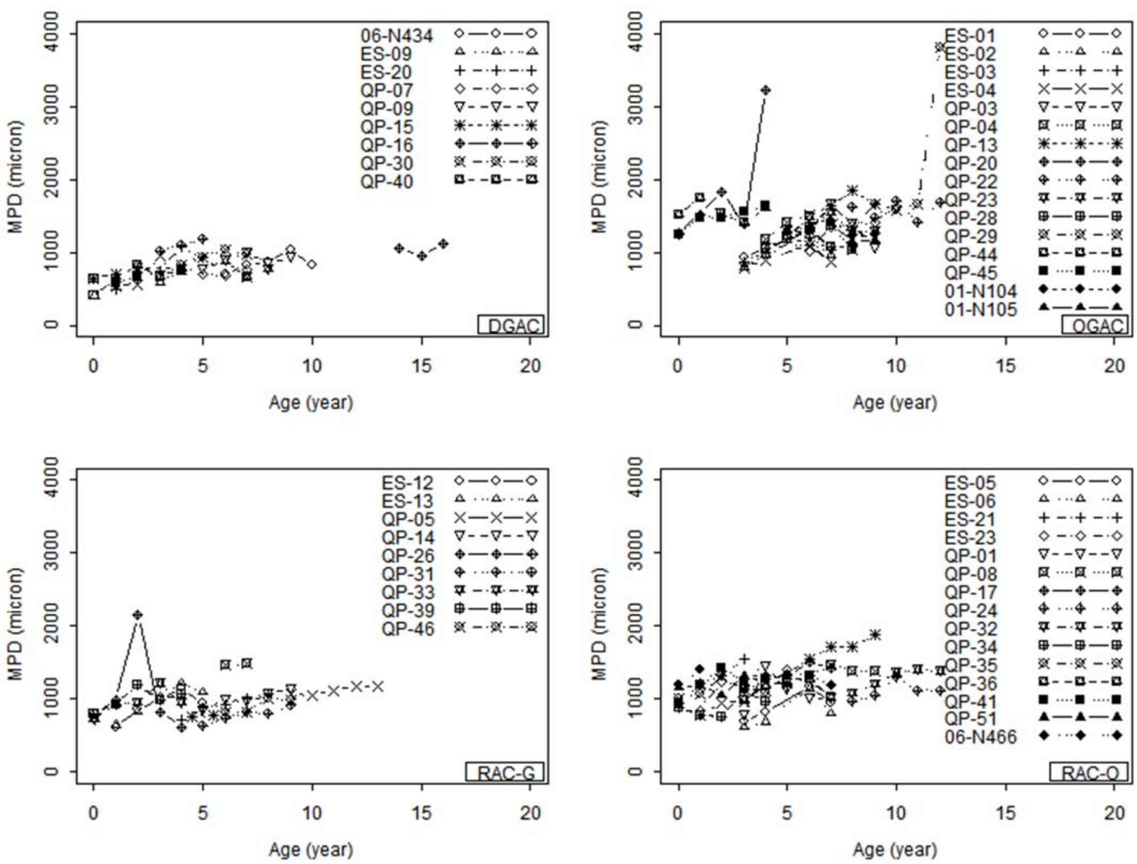

Figure 3.1: MPD trend over five years for each pavement section.

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

1. Among all the mixes investigated, F-mixes *(1, 2)* have the highest MPD. RAC-G mixes have higher MPD values than the dense-graded mixes, while open-graded mixes have higher MPD values than RAC-G mixes. Between the two open-graded mixes, OGAC mixes have higher MPD values than RAC-O mixes.
2. The R^2 for the RAC-G model is extremely low, probably because the RAC-G mixes show little change in macrotexture over the ages included in this study, indicating that they have not exhibited raveling. The R^2 of the models for the other three mixes are all above 0.50, and for the OGAC it is 0.80. The OGAC mix shows the greatest change in macrotexture over the ages included in this study, indicating that it has the highest propensity to ravel over time.
3. MPD generally increases with pavement age. For open-graded mixes, the age effect on macrotexture is more prominent on nonrubberized pavements (OGAC) than on rubberized pavements (RAC-O). The growth rate (with age) of MPD is significantly higher on OGAC pavements than on DGAC, RAC-G, and RAC-O pavements. The growth rates of MPD of RAC-G and RAC-O pavements are not statistically different from those of DGAC pavements.
4. Within each mix type, air-void content does not have a significant effect on the value of MPD.
5. Fineness modulus is significant in affecting the macrotexture of dense-graded pavements, and insignificant for RAC-O, RAC-G, and OGAC pavements.
6. Layer thickness is only significant on RAC-O pavements. Thicker RAC-O layers have higher macrotexture.
7. Mixes containing rubber have higher MPD values, most likely because the rubberized mixes include gap- and open-gradations, while the nonrubberized mixes include dense-gradations.

4 SOUND INTENSITY RESULTS

Tire/pavement noise was measured in all five survey years using the version of the On-board Sound Intensity method developed in California (OBSI-California). Since the OBSI-California method has been under continuous improvement during the project, variations of the method exist between years. Specifically, two Aquatred 3 test tires (designated as Aquatred 3 #1 and Aquatred 3 #2) were used in the first and second years, while three standard reference test tires (designated as SRTT#1, SRTT#2, and SRTT#4) were used in the third, fourth, and fifth 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 OBSI measurements. A summary of the field experiments and development of the calibration equations is presented in Appendix B.2. One thing to notice is that significant differences exist in the OBSI values measured with the two standard reference test tires (SRTT#1 and SRTT#4), as illustrated in Figure 4.1. In general, the sound intensities measured by SRTT#1 were higher than those measured with SRTT#4.

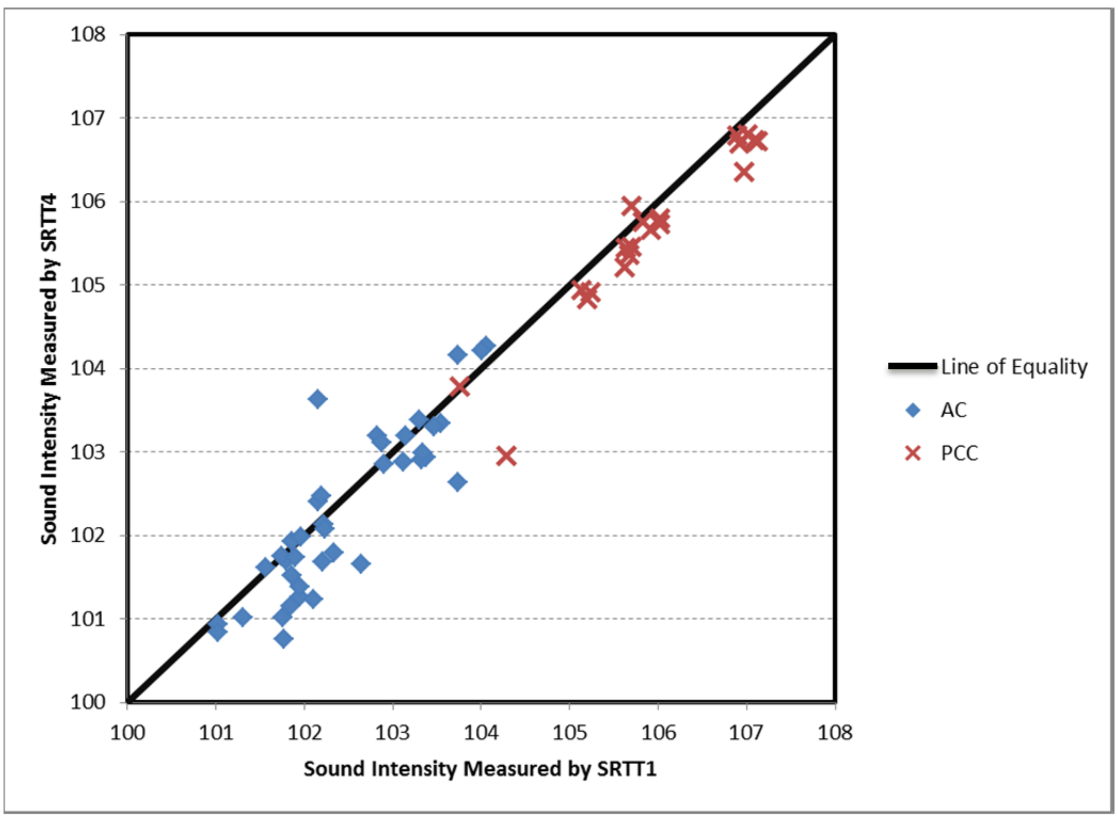

Figure 4.1: Comparison of overall OBSI values measured with SRTT#1 and SRTT#4.

With the developed calibration equations based on simple regression analysis, all sound intensity measurements were calibrated to their equivalent values at a reference condition (60 mph test car speed, Harmonie equipment, and SRTT#1). In the two-year and three-year study reports *(2, 8),* OBSI values were measured at a speed of 30 mph (48 km/h) on a few sections and were converted to their equivalent values at 60 mph (97 km/h) using calibration equations developed in the first two-year study report *(8).* Given the small number of sections on which the test speed was 30 mph and the potential for large errors to be introduced during the calibration for speed, UCPRC and Caltrans decided that in the analysis of the fourth-year and fifth-year data, all the OBSI measurements at 30 mph would be excluded from the analysis *(7)*. Pavement temperature corrections developed from the experiments were also not included because the standard error of the calibration equation was large relative to the size of the temperature correction.

The same air-density correction equations used in the first two years were applied to the data to account for the differences caused by variations of air density (a function of air temperature, humidity, and altitude) *(2,7).* Subsequent analysis and modeling were all based on the calibrated OBSI values corrected for tire type, analyzer, and air density.

Both the overall sound intensity and the sound intensities at one-third octave frequency bands were analyzed for this fifth-year report. Figure 4.2 shows the average overall OBSI values observed in the five survey years on each pavement section for the four mix types. Figure 4.3 shows the box plots of overall OBSI over five years for different mix types for 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 five years of data collected. Figure 4.5 through Figure 4.7 show the sound intensity spectra averaged by mix type and age group in the five survey phases. Generally, overall sound intensity increases with pavement age for all the surface mix types.

Regression analysis was conducted to determine the effects of mix properties, traffic, and weather conditions on sound intensity levels to develop prediction models for tire/pavement noise. Unlike the fourth-year report, surface distress data was not collected in the fifth year and MPD values were used as a surrogate for surface distress, and a set of new models were developed and discussed. The decision to not collect surface condition data was based on the fact that the visual surveys performed in previous years were highly variable, and the explanatory effect was not worth the time and cost.

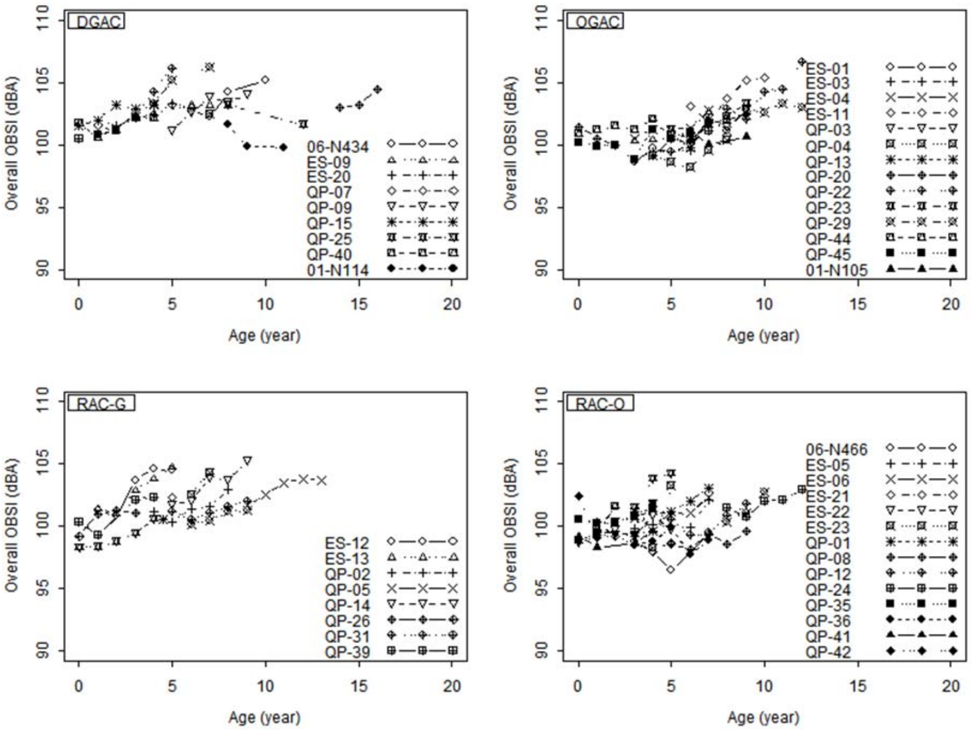

Figure 4.2: Trends of overall OBSI over five years for each pavement section.

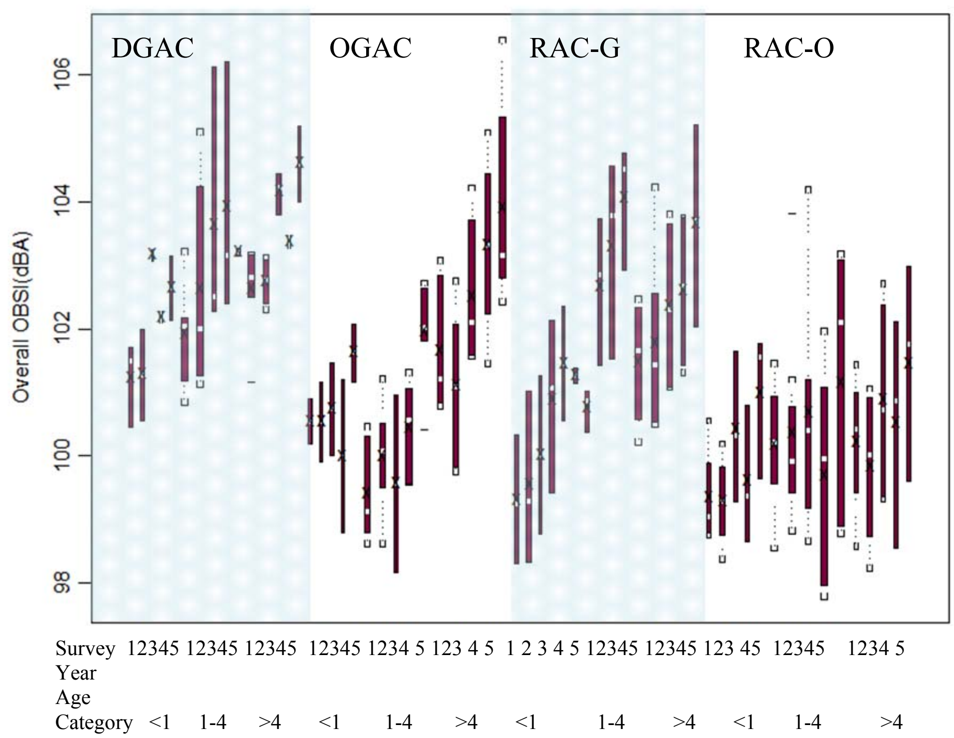

Figure 4.3: Comparison of overall OBSI values for different mix types for different initial age categories (Age Category) and for five years of data collection.

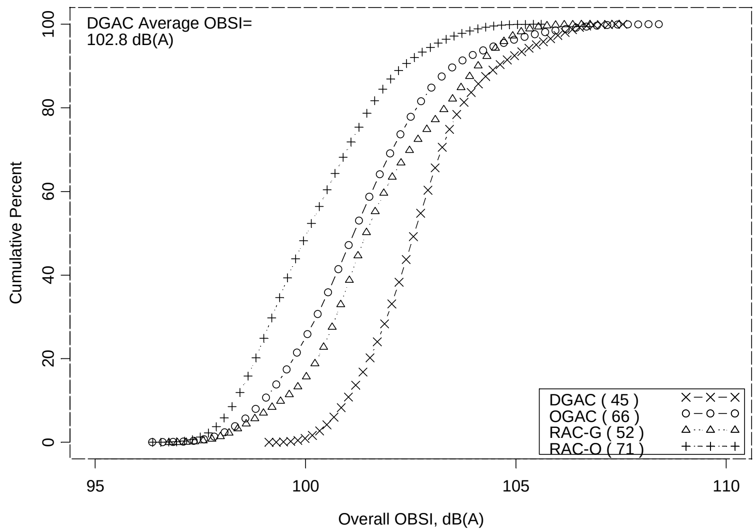

Figure 4.4: Estimated cumulative distribution function of overall OBSI of DGAC, OGAC, RAC-O, and RAC-G mixes.
(Note: **The numbers in parentheses in the legends represent the sample size of each mix type.)**

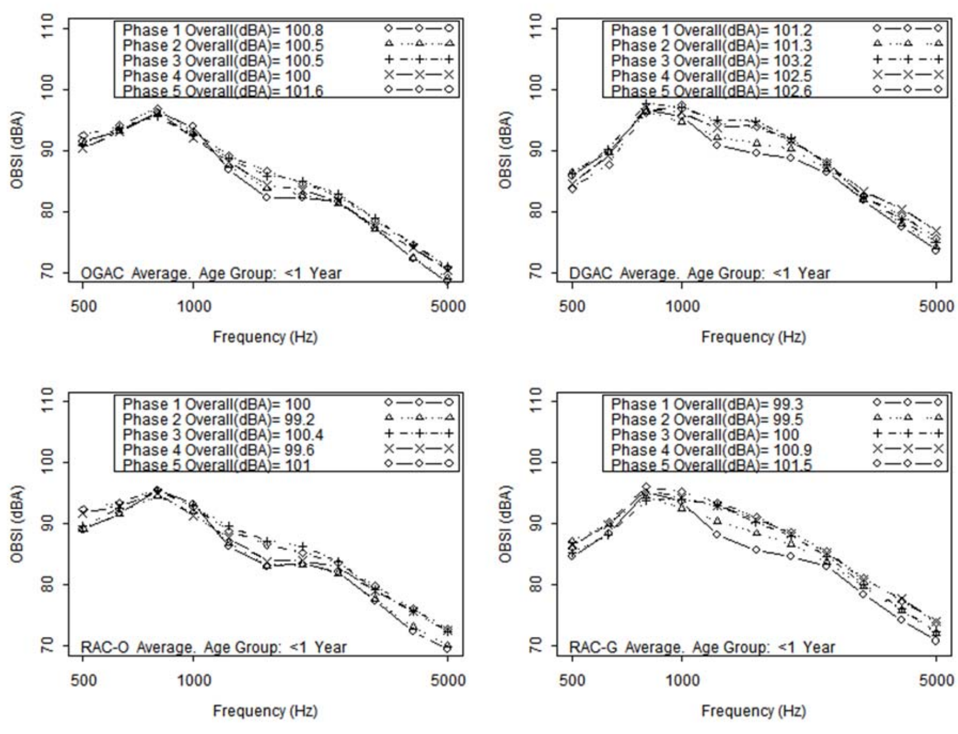

Figure 4.5: Average OBSI spectra for Age Group "<1 Year" in five survey phases (years).

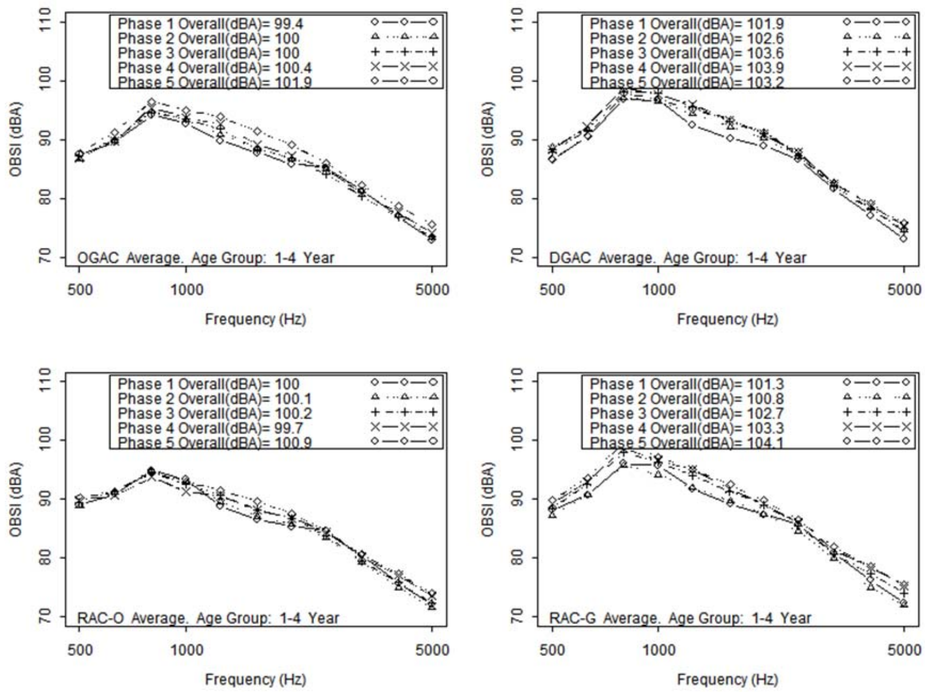

Figure 4.6: Average OBSI spectra for Age Group "1–4 Years" in five survey phases (years).

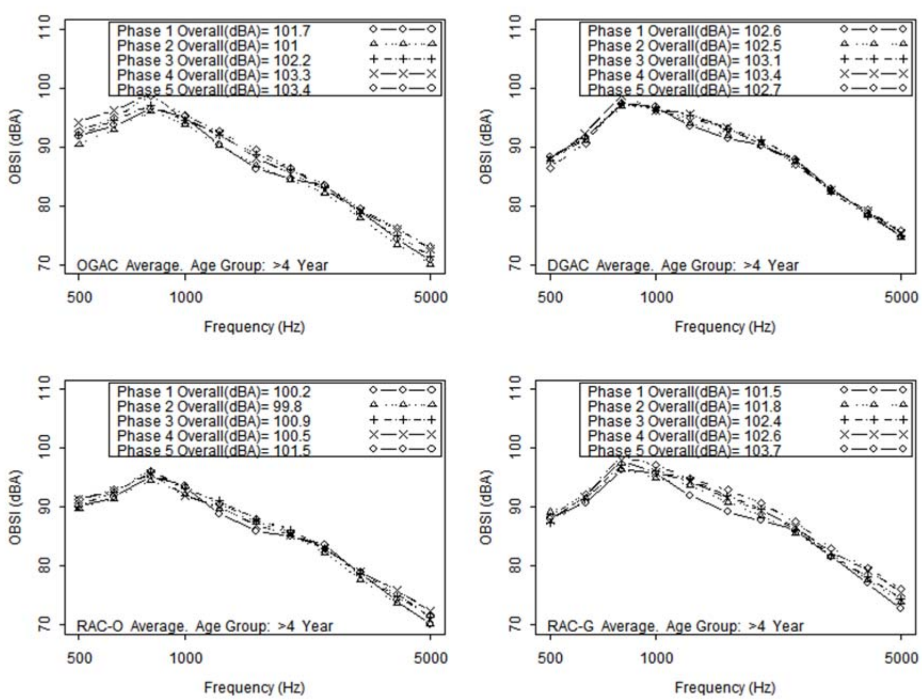

Figure 4.7: Average OBSI spectra for Age Group ">4 Years" in five survey phases (years).

Figure 4.8 shows the average annual rate of change for overall OBSI for the four mix types. It can be seen that the annual rate of change for RAC-O is quite a bit less than for the other three mix types. Figure 4.9 shows the average annual rate of change for overall OBSI by the initial ages of the sections in the study as well as mix type. It can be seen that the rate of change is generally lower for the younger sections, as expected.

Details of the analysis and modeling are presented in Appendix A.4, and the findings are summarized below. Models for all mixes combined and for each of the four 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.

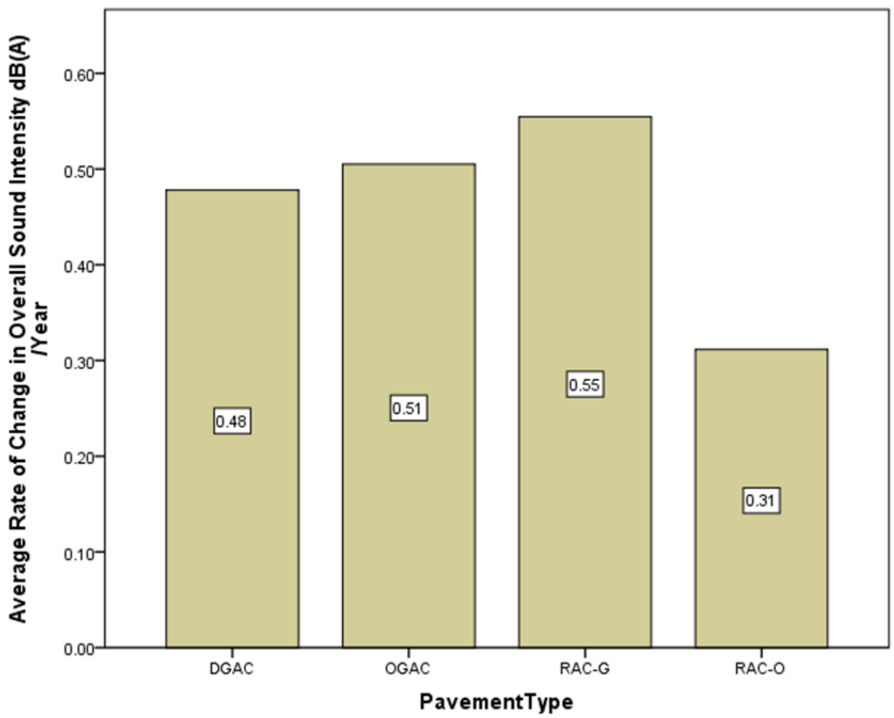

Figure 4.8: Average annual rate of change in overall OBSI for different mix types in five survey phases (years).

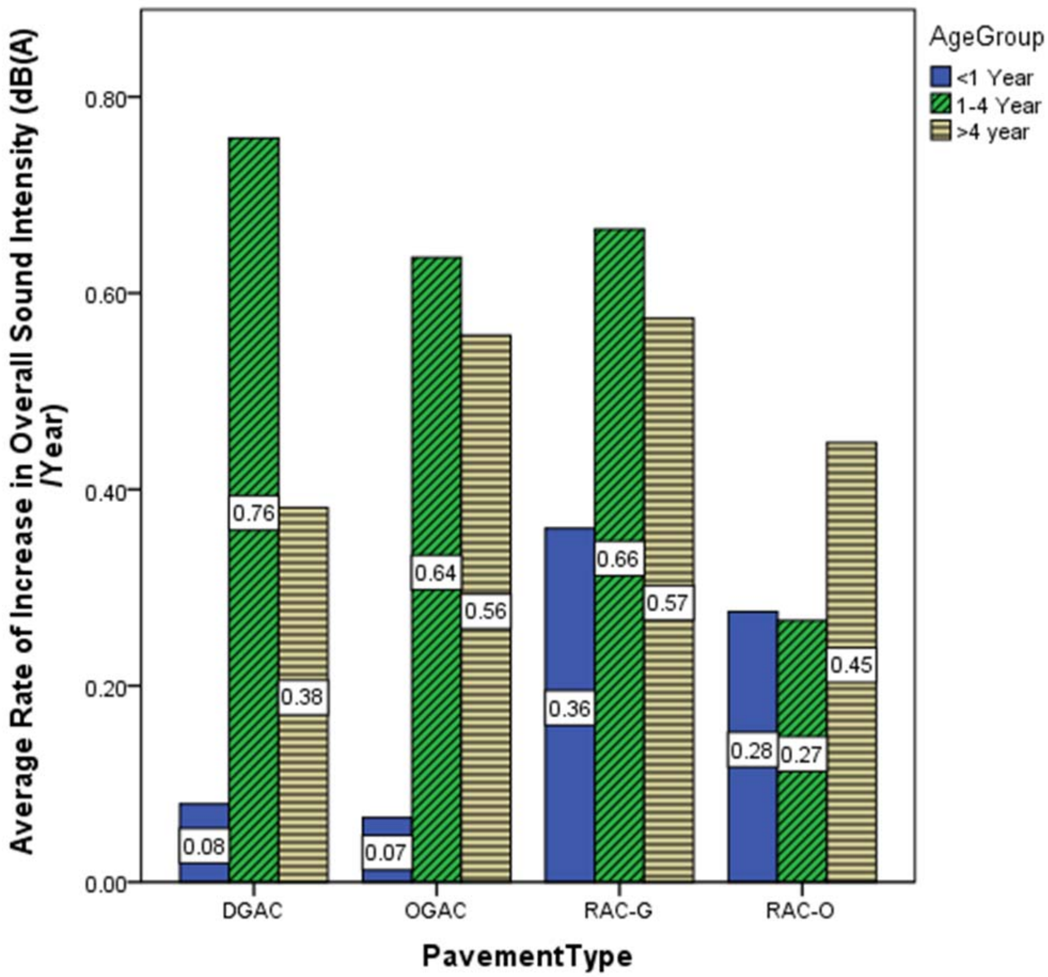

Figure 4.9: Average annual rate of change in overall OBSI for different age groups and mix types in five survey phases (years).

The following findings were obtained regarding overall sound intensity:

1. Overall tire/pavement noise generally increases with pavement age. The average noise level on DGAC pavements was about 101.3 dB(A) for newly paved overlays, 102.0 dB(A) for pavements between one and three years old, and between 103.3 and 103.9 dB(A) for pavements older than three years. 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. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes were about 3.7, 1.6, and 3.0 dB(A), respectively. After the pavements were exposed to traffic, the overall sound intensity measured on RAC-G pavements rapidly increased and became similar to what was been measured for DGAC pavements of similar ages. The overall sound intensity measured on the OGAC pavements did not change much for about six years and then began to increase more rapidly with pavement age. With a few

exceptions, the overall sound intensity measured on the RAC-O pavements did not change much for about seven years and then began to increase more rapidly with pavement age. For pavements with an age between five and seven years, RAC-O pavements have a noise-reducing ability superior to both RAC-G and OGAC. For pavements with an age between seven and nine years, RAC-O seems to be the only option that can still reduce noise levels by at least 3 dBA compared with DGAC of the same age. The ranking (from best to worst) of the four mix types in terms of noise reduction is RAC-O, OGAC, RAC-G, and DGAC.

2. New DGAC and OGAC mixes exhibit the lowest yearly rate of OBSI increase. For pavements that are one to four years old, DGAC, OGAC and RAC-G had the highest rates of increase. Over the full range of ages in the experiment, RAC-O pavements exhibited the lowest rate of increase in OBSI with about 0.31 dB(A) per year and RAC-G showed the highest rate of increase in overall OBSI with 0.55 dB(A) per year.
3. Multiple regression analysis with data from all mixes pooled together shows that overall sound intensity increases with increased MPD values (although not statistically significant) and decreases with the increased surface layer thickness. Multiple regression analysis showed that the rate of increase in overall sound intensity is statistically higher for OGAC pavements than the other two alternatives to DGAC. It was also noted that sections with a higher number of days with temperature greater than 30°C have a higher overall sound intensity. The R^2 for the overall OBSI model with all mixes pooled together was 0.54.
4. Multiple regression analysis on individual mix types (separate models for each mix type) was performed and the R^2 values were found to be relatively high, above 0.69 for all mixes except RAC-O, for which the R^2 was 0.45. The low coefficient of correlation for the RAC-O model is suspected to be due to the lack of much change in overall OBSI within the data set. Age was significant for OGAC and RAC-O but not for DGAC or RAC-G. The results show that the in-situ permeability (or air-void content) is only a significant factor for RAC-G mixes. Generally, higher permeability leads to a lower noise level. For all four mix types, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. 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. Relative truck traffic volume is a factor that significantly correlated with tire/pavement noise for DGAC and OGAC mixes. Thickness was found to be a significant factor for RAC-O mixes. Moreover, an increase in the thickness decreased the overall sound intensity.

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

1. At low frequencies (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. At a frequency level of 800 Hz, the sound intensities measured on OGAC, RAC-G, and RAC-O pavements began to become lower than those measured on DGAC pavements, with RAC-O having the lowest measured sound intensity. For

frequency levels equal to or above 1,000 Hz, the sound intensities measured on RAC-G pavements were generally lower than those measured on DGAC pavements.

2. For newly paved OGAC and RAC-O mixes, the sound intensities at the frequencies higher than 1,000 Hz remained constant with age in the first five years, but the sound intensities at low frequencies (630 to 800 Hz) increased with age. For newly paved DGAC and RAC-G mixes, the low frequency noise decreased slightly with age in the first five years, while the sound intensities at frequencies over 1,000 Hz increased with age.
3. For pavements with an initial age between one and four years, sound intensity increased slightly on both open-graded pavements (OGAC and RAC-O) for frequencies above 1,000 Hz. For frequencies below 1,000 Hz, sound intensity increased for RAC-G significantly while for other mix types it remained unchanged over five years.
4. For the oldest pavements (initial age greater than four years), the overall sound intensity with age for all mix types increased slightly. The increase of sound intensity with age mainly occurred at frequencies between 1,000 Hz and 2,500 Hz on 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 much increase over the entire range of the frequency spectrum.

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

1. For newly paved overlays (age less than or equal to one year), OGAC and RAC-O pavements exhibited a statistically higher 500-Hz noise level than DGAC pavements. RAC-G pavements had statistically the same level of 500-Hz sound intensity as DGAC pavements. Regarding the MPD values measured on these pavements, for newly-placed mixes, open-graded pavements had rougher surface textures that contributed to more tire vibration than dense- and gap-graded pavements. This rougher surface texture produced more noise at frequencies lower than 1,000 Hz. For pavements with ages between four and seven years, there was no significant difference in 500-Hz sound intensity among the four mixes. For old pavements (older than seven years), OGAC pavements had higher 500-Hz sound intensity than the other three pavement types, which indicates that OGAC pavements experienced more surface distresses that led to more tire vibration than the other pavement types. Both RAC-O and RAC-G pavements older than nine years old performed better than DGAC and could reduce noise up to 3 dB(A). OGAC pavements older than nine years old produced significantly more noise than DGAC pavements. Overall, the increase rate of 500-Hz sound intensity with age was lower on rubberized pavements (RAC-G and RAC-O) than on nonrubberized pavements (DGAC and OGAC).
2. Multiple regression analysis on all mixes pooled together shows that age, number of high temperature days, truck traffic in the coring lane, and MPD significantly affect the 500-Hz band sound intensity. The 500-Hz

band noise increased with pavement age, truck traffic volume, and MPD, but decreased with number of high temperature days.

3. Multiple regression analysis on individual mix type shows that truck traffic volume is a significant factor that contributes to the increase of 500-Hz band noise for open-graded mixes, but not for dense- or gap-graded mixes. The effect of truck traffic is significant for both types of open-graded mix, and the OGAC pavements were more sensitive to truck traffic than the RAC-O pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect the low-frequency noise. Air-void content significantly affects the 500-Hz noise intensity for OGAC mixes. MPD seems to be statistically significant for all mixes except OGAC pavements.

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

1. For newly paved sections, the 1,000-Hz sound intensity measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) was lower than the values measured on dense-graded pavements (DGAC). After the pavements were exposed to traffic, OGAC and RAC-O pavements had similar noise-reducing properties for about five years. After five years RAC-O pavements had a better sound-reducing effect than OGAC pavements. RAC-G pavements did not seem to have sound-reducing effect after they were exposed to traffic. For pavements older than one year, none of the mix types can provide 3 dB(A) noise reduction compared with DGAC of the same age.
2. Multiple regression analysis with all mixes pooled together 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 increased with pavement age and number of high temperature days, but decreased with layer thickness.
3. Multiple regression analysis on individual mix type shows that air-void content is not a significant factor for all pavements. For 1,000-Hz sound intensity, the surface layer thickness is significant for OGAC and RAC-O pavements at a 10 percent significant level and is not significant for DGAC and RAC-G pavements. The estimated parameters indicate that a thicker open-graded surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor for DGAC and RAC-O pavements. A higher MPD value corresponds to a higher noise level on DGAC, OGAC and RAC-G pavements, but a lower noise level on RAC-O pavements. Truck traffic is a significant factor for DGAC and OGAC pavements but not for RAC-G and RAC-O pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect the tire/pavement noise for any of the mixes.
4. In general, it is believed that much of the noise level at 1,000 Hz is controlled by the tread pattern of the tire, not the pavement.

The following findings were obtained regarding the 2,000 and 4,000-Hz band sound intensity:

1. For newly paved sections, the 2,000-Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) were significantly lower than the values measured on dense-graded pavements (DGAC). The 2,000-Hz sound intensity increased at all pavement ages on RAC-G pavements, but primarily in the early years only for DGAC, OGAC and RAC-O pavements. The rate of increase in sound intensity at 2,000 Hz with age was the lowest for RAC-O pavements.
2. The 4,000-Hz sound intensity level for OGAC and RAC-O was significantly lower than DGAC and RAC-G for newly paved and sections older than four years. For sections between three and nine years old, RAC-O and OGAC pavements can provide up to an 11 dB(A) reduction in sound intensity. For sections older than the nine years, RAC- O seems to be the only option to provide a 3 dB(A) sound-intensity reduction.
3. For all pavement types, the 4,000-Hz sound intensity of newly paved sections increased with age. For old sections, however, the rate of increase in high frequency sound intensity was more pronounced for RAC-G sections.
4. Multiple regression analysis with all mixes pooled together shows that age, mix type, number of high temperature days, and MPD significantly affect the 2,000-Hz band sound intensity. The 2,000-Hz band noise increased with pavement age and number of high temperature days, but decreased with MPD.
5. Multiple regression analysis with all mixes pooled together shows that age, mix type, number of high temperature days, layer thickness, MPD, and truck traffic significantly affect the 4,000-Hz band sound intensity. The 4,000-Hz band noise increased with pavement age, number of high temperature days, layer thickness, and truck traffic, but decreased with MPD.
6. For 2,000-Hz sound intensities, multiple regression analysis on individual mix type shows that air-void content is a significant factor for OGAC and RAC-G pavements, and is not significant for RAC-O and DGAC pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on any pavement type except RAC-O. For RAC-O pavements, a larger fineness modulus (coarser gradation) resulted in significantly lower tire/pavement noise in the 2,000-Hz band. Truck traffic is a significant factor for all pavement types and the 2,000 Hz sound intensity increases with an increase in truck traffic.
7. For 4,000-Hz sound intensities, multiple regression analysis on individual mix type shows that air-void content is only significant for DGAC pavements. An increase in the air-void content of DGAC mixes decreases the 4,000 Hz high frequency sound intensity. Higher truck traffic volume is significant for all mixes except RAC-G. Higher truck traffic leads to a higher 4,000-Hz noise level. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on all pavement types except RAC-O pavements. A higher fineness modulus for RAC-O pavements resulted in a lower 4,000 Hz sound intensity. Pavement surface macrotexture (MPD) is significant on both OGAC and RAC-O

pavements, and higher MPD values led to a lower 4,000-Hz noise level. However, MPD was somewhat correlated with air-void content, and it is likely that the effect shown for MPD was at least partly related to higher air-void contents. Number of high temperature days is only significant for OGAC and RAC-G pavements, and a greater number of high temperature days resulted in a lower 4,000-Hz sound intensity.

5 ENVIRONMENTAL SECTIONS RESULTS

Twenty-one environmental test sections (labeled as "ES" in this study) were constructed by Caltrans to test pavement noise, durability, permeability, and friction performance trends for new types of surface mixes. They include both new asphalt mixes—such as Type G-MB, Type D-MB, RUMAC-GG, and EU gap-graded mixes—and currently used mixes—OGAC, RAC-O, DGAC, and RAC-G—placed as controls at some locations. For more information, see Appendix B.1. Detailed descriptions of the mixes are included in the two-year noise study report *(2)*.

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

- Based on the Fresno 33 sections, RAC-G and Type G mixes generally exhibited the highest and lowest MPD values, respectively. RAC-G and RUMAC-GG exhibited higher IRI values than Type G-MB, Type D-MB, and DGAC mixes. There was no indication of the effect of the layer thickness on the measures IRI and MPD. Tire/pavement noise increased significantly in the fifth survey year on the RAC-G 45 mm, DGAC, and RUMAC-GG 45 mm. RAC-G 45 mm mixes exhibited the highest noise level with 104.7 dB(A) and the Type G-MB 45 mm mixes exhibited the lowest noise intensity with the value of 102.7 dB(A). None of these mixes can provide any noise reduction compared to the DGAC mix over the long run.
- The San Mateo 280 section performed better than the Sacramento 5 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, it was found that RAC-O mixes have the highest IRI values. Open-graded mixes, OGAC, had the lowest noise levels among all the mix types over the five survey years, but each exhibited a major increase in overall sound intensity. The performance of BWC mixes was more similar to DGAC mixes than to open-graded mixes. No interaction between noise-reducing properties and thickness was observed. However, the BWC mixes at LA 138 are not considered by industry to be representative of other BWC mixes in the state.
- The EU-GG mix performed relatively well in terms of providing sound-reducing benefits. The year-to-year increase in IRI for these mixes is not significant.

- The Yolo 80 section still provides good ride quality according to FHWA guidelines but has lost its noise-reducing capabilities.
- Almost all BWC sections provide good ride quality for interstate pavements.
- Polymer-modified open-graded BWC mixes rapidly lost their noise-reduction advantage, whereas polymer-modified gap-graded BWC mixes can maintain their noise-reduction advantage for a longer period.

6 CONCLUSIONS

This study compares five consecutive 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).[3] Since the start of the study, these materials have been renamed as OGAC, rubberized hot-mix asphalt open-graded (RHMA-O), rubberized hot-mix asphalt gap-graded (RHMA-G) and hot-mix asphalt (HMA). The original names have been used throughout this report. Categories of data include tire/pavement noise, ride quality, and macrotexture. The five years of data were analyzed in this report with the following 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 equations 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

It should be noted that in the fifth year report the models developed in the fourth year report were updated with fifth year data, and previous surface condition variables (rutting, fatigue cracking) were removed from the models because of difficulties with the year-to-year consistency of visual condition surveys. MPD, however, was introduced into individual models as an indication of raveling. As with the fourth-year report, two types of models were developed. In the first type, data for all the mixes were pooled and the models were developed from them. In the second type, the models were developed for individual mixes using data from all five years.

6.1 Performance of Open-Graded Mixes

As was found in the fourth-year report, for newly paved overlays, the OGAC, RAC-G, RAC-O open-graded mixes had lower tire/pavement noise than DGAC mixes by average levels of 3.7 dB(A), 1.6 dB(A), and 3.0 dB(A), respectively. For comparison, the average tire/pavement noise level was approximately 101.3 dB(A) for newly paved DGAC overlays *(7)*.

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[3] See Footnote 1 on page 18 regarding terminology for pavement types used in this report.

After the pavements were exposed to traffic, this noise benefit generally diminished slightly for about seven to nine years for OGAC. RAC-O was quieter than OGAC and kept a noise-reduction benefit longer than OGAC. For pavements older than nine years, although no RAC-O pavement was found to provide a noise-reduction benefit of 3 dB(A) or more, there was still a noise-reduction benefit observed for RAC-O pavements compared with DGAC of the same age, with 50 percent of RAC-O pavements 2 dB(A) quieter than DGAC pavements.

Newly paved open-graded OGAC and RAC-O overlays generally had higher low-frequency noise and lower high-frequency noise than dense-graded mixes. In the first five years after the OGAC mixes were exposed to traffic, high-frequency noise increased with age due to the reduction of surface permeability and air-void content under traffic. Low-frequency noise increased with age, likely due to the increase in surface distresses, primarily raveling. This effect was less pronounced for RAC-O pavements. For the open-graded mixes, OGAC and RAC-O, between one and four years old, a large increase in high frequency noise between 1,000 Hz and 2,500 Hz was observed after five years.

MPD was initially lower for RAC-O than for OGAC and increased more slowly on RAC-O pavements than on OGAC pavements. IRI had lower initial values and increased more slowly on RAC-O pavements than on OGAC pavements.

6.2 Performance of RAC-G Mixes

The newly paved RAC-G mixes were quieter than an average newly paved DGAC mix by about 1.8 dB(A) *(7)*. 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. Old RAC-G pavements had a higher rate of increase in overall noise intensity of 0.56 dB(A) per year compared to DGAC pavements which had a noise increase rate of 0.38 dB(A) per year. Among newly paved overlays, 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. For RAC-G pavements older than three years, noise of all frequencies increased with age but more on the low-frequency side of the frequency spectrum.

The IRI values on newly paved RAC-G mixes were higher those on DGAC mixes. The rate of increase in IRI for RAC-G mixes was smaller than for DGAC mixes. Therefore, older RAC-G mixes had lower IRI values compared to their DGAC counterparts. The MPD value on newly paved RAC-G mixes was higher than on DGAC mixes. The rate of increase in MPD was similar for both RAC-G and DGAC.

6.3 Performance of Environmental Sections

During the fifth year of noise study, the noise, ride quality, and surface macrotexture of twenty-three environmental sections were collected and following conclusions were drawn:

Based on the Fresno 33 sections, the RAC-G and Type G-MB mixes generally exhibited the highest and lowest MPD values, respectively. RAC-G and RUMAC-GG exhibited higher IRI values than the Type G-MB, Type D-MB, and DGAC mixes. There is no indication of the effect of layer thickness on the measured IRI and MPD. Type G-MB 45 mm thick overlays exhibited the lowest sound intensity, with a value of 102.7 dB(A) in the fifth year of data collection. None of these mixes provided any noise reduction compared to the DGAC mix after three years.

Between the two sections with thin RAC-O overlays on concrete pavement, the San Mateo 280 section performed better after five years than the Sacramento 5 sections in terms of both noise and roughness, possibly due to its greater layer thickness 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 of data collection.

From the LA 138 test sections, which include sections with DGAC, OGAC, RAC-O, and BWC mixes, it was found that RAC-O mixes have the highest IRI values, and OGAC mixes have the lowest noise levels among all the mix types over the five survey years.

The EU-GG mix on LA 19 performed well in terms of providing sound-reduction benefits compared with the statewide data for DGAC. The year-to-year increase in IRI for this mix is not significant.

The Yolo 80 section still provides good ride quality according to FHWA guidelines but has lost its noise-reducing capabilities compared with statewide data for DGAC.

Almost all BWC sections provide good ride quality for interstate pavements. Polymer-modified open-graded BWC mixes rapidly lose their noise-reduction advantage, whereas polymer-modified gap-graded BWC mixes can maintain their noise reduction advantage for a longer period.

6.4 Variables Affecting Tire/Pavement Noise

The findings from this fifth year of the study regarding variables that affect tire/pavement noise are generally in agreement with the significant factors found in the earlier reports *(2, 3, 7).* That is, tire/pavement noise is greatly influenced by surface mix type and mix properties, age, traffic volume, and the presence of distresses indicated by MPD, which served as a substitute for raveling in this study. 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 all the mix types (DGAC, RAC-G, OGAC and RAC-O), the aggregate gradation variable (fineness modulus) or nominal maximum aggregate size (NMAS) did not seem to significantly affect tire/pavement noise. It should be noted that this conclusion is based on the 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 since greater MPD is typically associated with higher air-void content.

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APPENDICES

APPENDIX A: DETAILS OF FIVE-YEAR DATA PRESENTATION AND ANALYSIS

A.1: Introduction

This appendix presents the details of data plotting and analysis based on the pool of five-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 the IRI answers these questions:

- What pavement characteristics affect IRI?
    - Are initial IRI and IRI changes with time different for rubberized and nonrubberized 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 2.1 shows the average IRI measured in five consecutive years for individual pavement sections of four mix types: DGAC, OGAC, RAC-G, and RAC-O. It should be noted that the IRI values at the time the overlays were constructed or soon thereafter are unknown except for those sections that were tested soon after construction. The original condition of the pavement layers beneath the overlays is also unknown.

Almost all sections exhibit an upward trend in IRI indicating that the road surface becomes rougher over time. A major decrease in IRI for QP-26 (RAC-G) and a significant increase in IRI for QP-20 (OGAC) may be due either to difficulties in measurement (such as problems retracing the earlier wheelpath) or to road maintenance. These sections are treated as outliers and have been removed from the subsequent analysis.

Figure A.1 is a box plot that shows the variation in IRI values for different mix types across all five 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 purple box are the 75th and 25th percentiles respectively, and the upper and lower brackets are the upper and lower extreme values respectively.

According to the plot, the average IRI values of the different mixes are close to each other, and most of the sections have acceptable IRI values based on the FHWA criterion of 170 in./mi (2.4 m/km) *(1).* However, one OGAC pavement in fifth year shows high IRI values (>3.6 m/km) that would trigger Caltrans maintenance action.

Figure A.2 shows the IRI values for different mix types for the three initial age categories of less than one year, one to four years, and greater than four years. It can be seen that IRI values increase with age for RAC-O and DGAC mixes but show no specific trend for OGAC and RAC-G mixes.

Figure A.3 shows the time trend of IRI across the five years of data collection for different mix types for the three initial three age categories. IRI generally increases with time. For newly paved mixes (Age Category "<1 year"), IRI varied slightly for DGAC, OGAC, and RAC-O in the first five years, and RAC-G had the lowest IRI values, but OGAC and RAC-G showed a significant increase in IRI in the fifth year after construction. From Figure 2.1 it can be seen that this is due to the rapid increase in IRI on one pavement section of each pavement type. For RAC-G it is Section QP-26, which is located on Interstate-280 in Santa Clara County in Caltrans District 4, and for OGAC it is Section QP-20, which is located on Highway 152 in Santa Cruz County in District 5. The reason for the rapid increase in IRI at these sections is unknown. If QP-20 and QP-26 are excluded, IRI also varied slightly for OGAC and RAC-G (Figure A.4).

(Note: IRI values have been reported in m/km since data collection began. 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	170	2.68
FHWA "mediocre" for non-Interstate maximum value	220	3.47
Caltrans rigid pavement PMS prioritization trigger	213	3.36
Caltrans flexible pavement PMS prioritization trigger	224	3.54

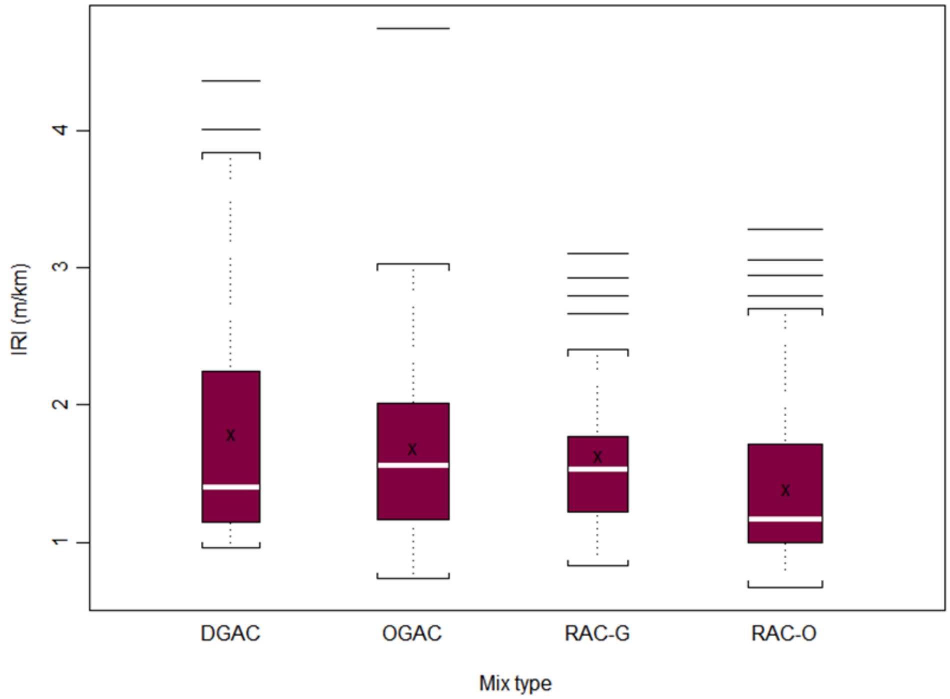


Figure A.1: Variation in IRI values for different mix types for all five years of pooled data and all initial ages.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

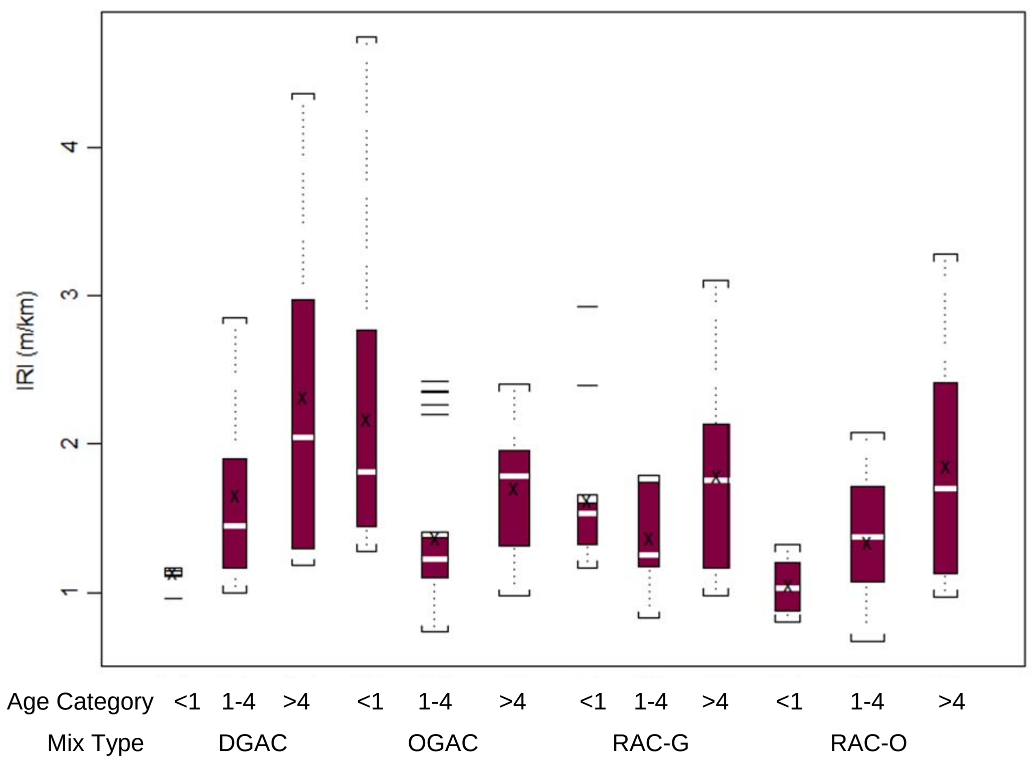


Figure A.2: Variation in IRI values for different mix types for different initial ages (Age category in years) for all five years of pooled data.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

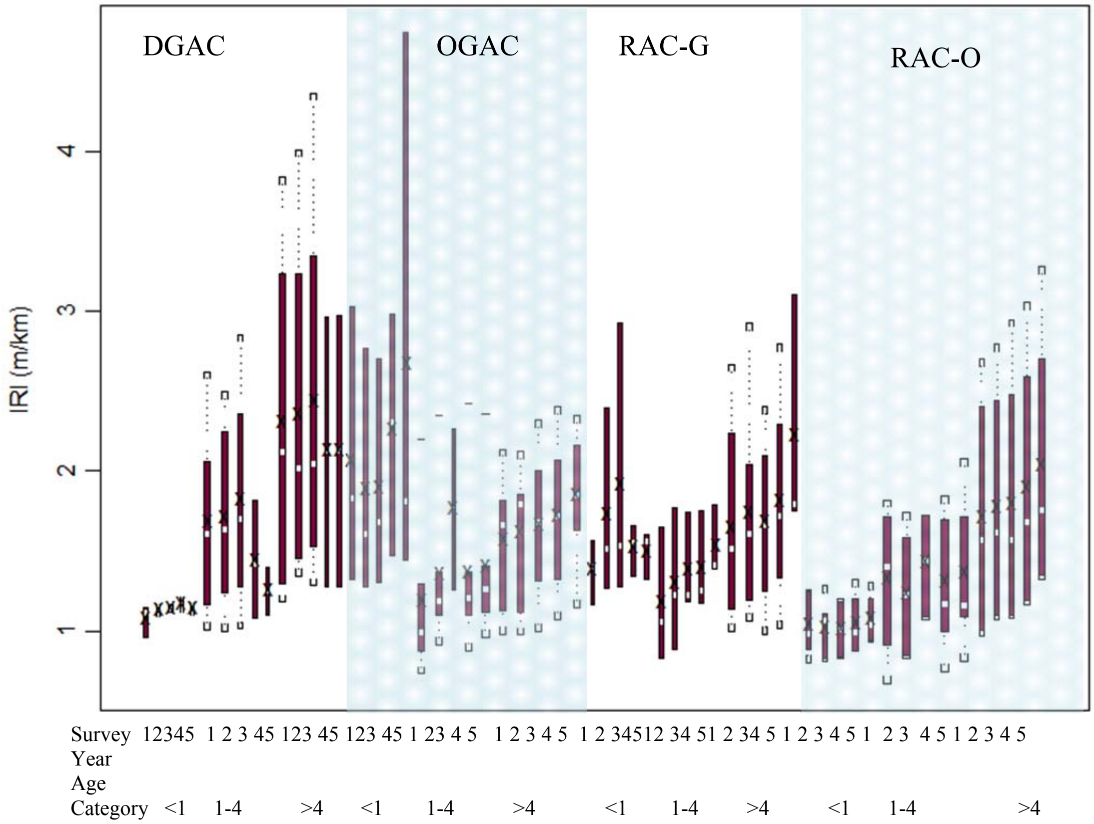


Figure A.3: Comparison of IRI values for different mix types at different ages for five years of data collection.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

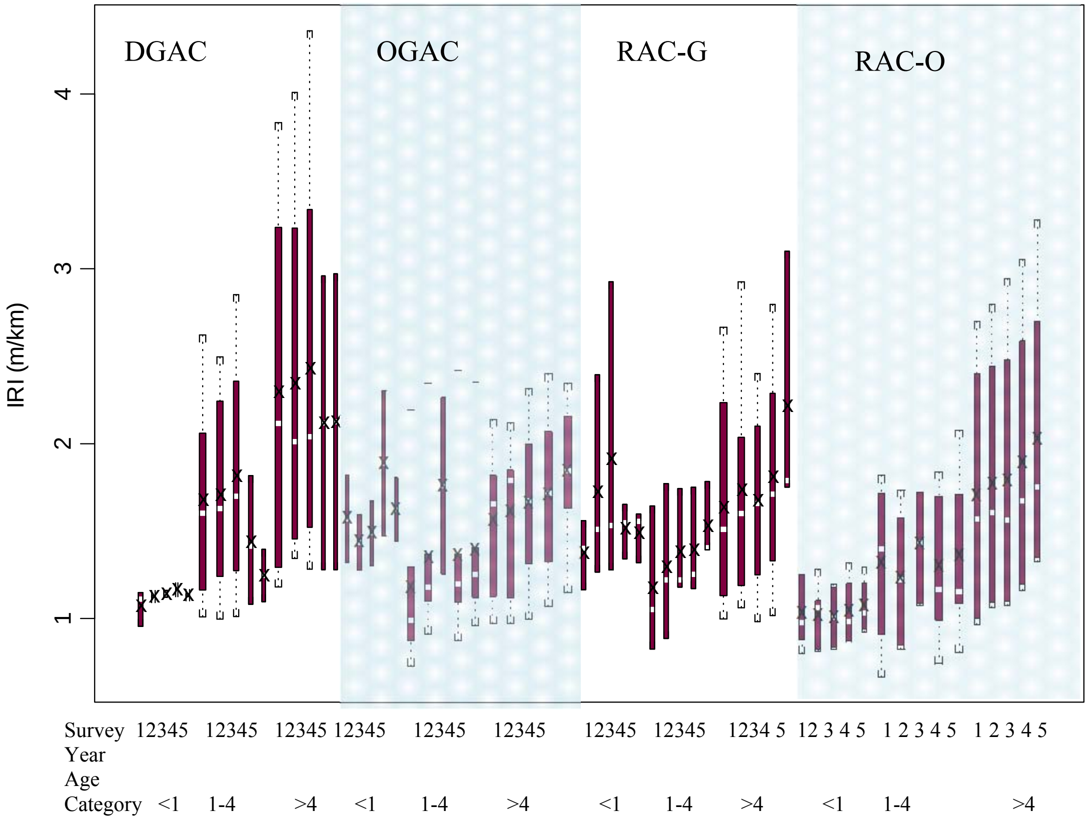


Figure A.4: Comparison of IRI values for different mix types at different ages for five years of data collection after removing QP-20 and QP-26.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

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 fifth 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. The 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 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.

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

Model Number	Name	Coefficient	P-value	Constant Term	R-squared
1	**Age(years)**	9.6E-02	**0.000**	1.04	0.17
2	Air-void Content (%)	-1.9E-02	0.141	1.76	0.02
3	**Mix Type**	-3.9E-01	**0.003**	1.91	0.09
4	**Rubber Inclusion**	-2.5E-01	**0.006**	1.68	0.03
5	MPD(microns)	2.2E-04	0.066	1.31	0.01
6	Average Annual Rainfall(mm)	2.0E-04	0.051	1.44	0.02
7	Age*Average Annual Rainfall(mm)	2.9E-02	0.230	1.08	0.25
8	**Average Annual Wet Days**	2.3E-03	**0.027**	1.40	0.02
9	Age*Average Annual Wet Days	5.2E-02	0.104	0.97	0.22
10	**Average Annual Maximum Daily Air Temp (C)**	-8.9E-02	**0.000**	3.63	0.11
11	Annual Number of Days > 30C	-4.0E-03	**0.000**	1.87	0.09
12	Annual Degree-Days > 30C	-1.1E-04	**0.000**	1.87	0.09
13	Annual FT Cycles	-6.6E-03	0.065	1.64	0.01
14	**AADT**	1.5E-06	**0.042**	1.47	0.02
15	**Annual ESALs per Coring Lane**	-1.1E-07	**0.047**	1.61	0.02

Based on the results in Table A.1, multiple regression analysis was conducted to account for the effect of various factors simultaneously. First a pair-wise correlation analysis was performed to avoid 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. Average Annual Maximum Daily Air Temperature is highly correlated with Annual Number of Days >30ºC and Annual Degree-Days >30ºC. AADTT per Coring Lane is highly correlated with Annual ESALs per Coring Lane. 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 nonconstant 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 is 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.

In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as independent variables, while the mix property variables are 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 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)	0.87380	0.0364	23.977	0
Age	-0.02100	0.0028	-7.4315	0
MixTypeOGAC	0.07140	0.0241	2.965	0.0033
MixTypeRAC-G	0.02180	0.0249	0.8768	0.3815
MixTypeRAC-O	0.11330	0.0234	4.8398	0
AvgAnnualRainfall	-0.00010	0	-2.7751	0.006
NoDaysTempGT30	0.00060	0.0002	3.3334	0.001
AADTTCoringLane	0	0	-1.6643	0.0974
AnnualFTCycles	0.0023	0.0007	3.1015	0.0022

Residual standard error: 0.123 on 232 degrees of freedom; Multiple R-Squared: 0.38.

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 0.38 compared to 0.35 in the fourth-year report, it does not do a very good job of predicting IRI. It can be seen that 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 have lower initial IRI than DGAC, but only OGAC and RAC-O are statistically significantly different from DGAC.

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

For DGAC pavements:

$$\begin{aligned}1/\sqrt{IRI}\,(m/km) &= 0.8953 - 0.0165 \times Age(year) - 0.0004 \times MPD - 0.0255 \times \log(Permeability)(cm/\sec) \\ &-0.0001 \times AverageAnnualRainfall(mm) + 0.0002 \times NumberOfDays > 30C \\ &+0.0025 \times AnnualFTCycles\end{aligned} \qquad \textbf{(A.2.2)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	0.8953	0.1425	6.2832	0
Age	-0.0165	0.008	-2.0762	0.0525
MPD	-0.0004	0.0002	-2.2194	0.0395
logPerm	-0.0255	0.0158	-1.6065	0.1256
AvgAnnualRainfall	-0.0001	0	-1.2762	0.2181
NoDaysTempGT30	0.0002	0.0005	0.4525	0.6563
AADTTCoringLane	0	0	0.929	0.3652
AnnualFTCycles	0.0025	0.0023	1.0825	0.2933

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

For OGAC pavements:

$$\begin{aligned}1/\sqrt{IRI}\,(m/km) &= 0.9993 + 0.0507 \times Age(year) - 0.0005 \times MPD(micron) + 0.0173 \times \log(Permeability)(cm/\sec) \\ &+0.0001 \times AverageAnnualRainfall(mm) + 0.0016 \times NumberOfDays > 30C \\ &+0.0018 \times AnnualFTCycles\end{aligned} \qquad \textbf{(A.2.3)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	0.9993	0.2539	3.9359	0.0006
Age	0.0507	0.0256	1.9786	0.0594
MPD	-0.0005	0.0002	-2.3199	0.0292
logPerm	0.0173	0.0216	0.8039	0.4294
AvgAnnualRainfall	0.0001	0.0002	0.6511	0.5212
NoDaysTempGT30	0.0016	0.0007	2.353	0.0272
AADTTCoringLane	0	0	-0.4835	0.6331
AnnualFTCycles	0.0018	0.0023	0.7701	0.4487

Residual standard error: 0.1101 on 24 degrees of freedom; Multiple R-Squared: 0.48.

For RAC-G pavements:

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

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

	Value	Std. Error	t value	P-value
(Intercept)	1.1305	0.0898	12.59	0
Age	-0.0099	0.0103	-0.9612	0.3469
MPD	-0.0003	0.0001	-3.5741	0.0017
logPerm	-0.0161	0.0118	-1.3612	0.1872
AvgAnnualRainfall	-0.0001	0.0001	-1.4321	0.1662
NoDaysTempGT30	0.0007	0.0004	1.6473	0.1137
AADTTCoringLane	-0.0001	0	-2.8224	0.0099
AnnualFTCycles	0	0.002	0.0181	0.9858

Residual standard error: 0.08693 on 22 degrees of freedom; Multiple R-Squared: 0.68.

For RAC-O pavements:

$$1/\sqrt{IRI}\,(m/km) = 0.8137 - 0.0402 \times Age(year) + 0.0001 \times MPD(micron) - 0.0214 \times \log(Permeability)(cm/\sec) + 0.0007 \times NumberOfDays > 30C + 0.003 \times AnnualFTCycles \quad \textbf{(A.2.5)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	0.8137	0.218	3.7321	0.0007
Age	-0.0402	0.0131	-3.0771	0.0042
MPD	0.0001	0.0001	0.6386	0.5275
logPerm	-0.0214	0.0268	-0.7997	0.4296
AvgAnnualRainfall	0	0.0001	0.0006	0.9996
NoDaysTempGT30	0.0007	0.0007	1.0475	0.3025
AADTTCoringLane	0	0	-0.5954	0.5556
AnnualFTCycles	0.003	0.0022	1.3694	0.1801

Residual standard error: 0.1359 on 33 degrees of freedom; Multiple R-Squared: 0.41.

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. The results show that for DGAC, OGAC, and RAC-G pavements, MPD is significant at the 95 percent confidence level. An increase in MPD increases the IRI values in these mixes. For RAC-O pavements, IRI decreases with MPD, but is not significant. IRI on OGAC pavements decreases with the number of days greater than 30ºC, indicating that open-graded pavements are smoother in high temperature regions than in low temperature regions. It is not clear why this occurs, but may also have to do with typical temperatures at the time of paving. Traffic volume is a significant variable for RAC-G pavements and higher traffic volume leads to a higher IRI.

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 below 0.45.
2. Except for an old DGAC pavement, all sections are smoother than the old Caltrans Pavement Management System IRI trigger criterion of 3.6 m/km (224 in./mi). Many older DGAC pavements are rougher than the current PMS IRI trigger of 2.7 m/km (170 in./mi), and a few of the other mix types also exceed the new threshold.
3. Rubberized open-graded mixes have lower initial IRI values than nonrubberized open-graded mixes; rubberized gap-graded mixes have lower initial IRI values than nonrubberized dense-graded mixes.
4. The surface types OGAC, RAC-G, and RAC-O all have lower initial IRI than DGAC, but only OGAC and RAC-O are statistically significantly different from DGAC. Monitoring over five years indicates that IRI increases with age on DGAC, RAC-G, and RAC-O pavements, but that age has a statistically significant effect on increasing IRI on OGAC, DGAC, and RAC-O at only a 10 percent significance level.
5. Open-graded pavements (OGAC and RAC-O) are smoother in high temperature regions than in low temperature regions.
6. The IRI of DGAC, OGAC, and RAC-G pavements increases with increasing MPD, and the effect of MPD is significant. 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 the MPD answers these questions:

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

The 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 in five consecutive years for individual pavement sections for four mix types: DGAC, OGAC, RAC-G, and RAC-O. Some of the sections, whose numbers are listed in the legend, showed lower MPDs in the later years, but the differences were small and can be attributed to measurement errors or other random variations. A few sections, however, showed significantly different MPD values. These sections include the two OGAC pavements that were newly paved at the start of the study, QP-20 and QP-29. These two newly paved OGAC sections both showed significantly high terminal MPD values. Section QP-20 is located on a steep hill and may have experienced compaction problems during construction that led to the high MPD. QP-29 is on Highway 16 in District 3 near Sacramento where both annual rainfall and traffic volume are low, and the reason for the high MPD value remains unclear. Consequently, these two sections are treated as outliers and will be removed from the statistical analysis.

Figure A.5 shows the variation in MPD values for the different mix types, including two F-mixes, based on the five-year survey data. The information conveyed in the plots is the similar to that in the plot based on the first four years of survey data *(3, 6)*. The two F-mixes have the highest MPD. The RAC-G mixes have higher MPD values than the dense-graded mixes, while the open-graded mixes have higher MPD values than the RAC-G mixes. Between the two types of open-graded mixes, the OGAC mixes have higher MPD values than the RAC-O mixes.

Figure A.6 shows the time trend of MPD in five years for different mix types for three age categories. As the figure shows, MPD generally increases with pavement age for the same pavement section.

A.3.2: Regression Analysis

Regression analysis was performed to evaluate the effects of traffic, climate, and pavement materials on MPD values. Due to lack of data, the effect of pavement surface condition was not considered in the fifth year study. First, a single-variable regression analysis was conducted to prescreen 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.7. The P-values less than 0.05 are shown in bold type. Descriptions of the variables are provided in References *(1, 3)*.

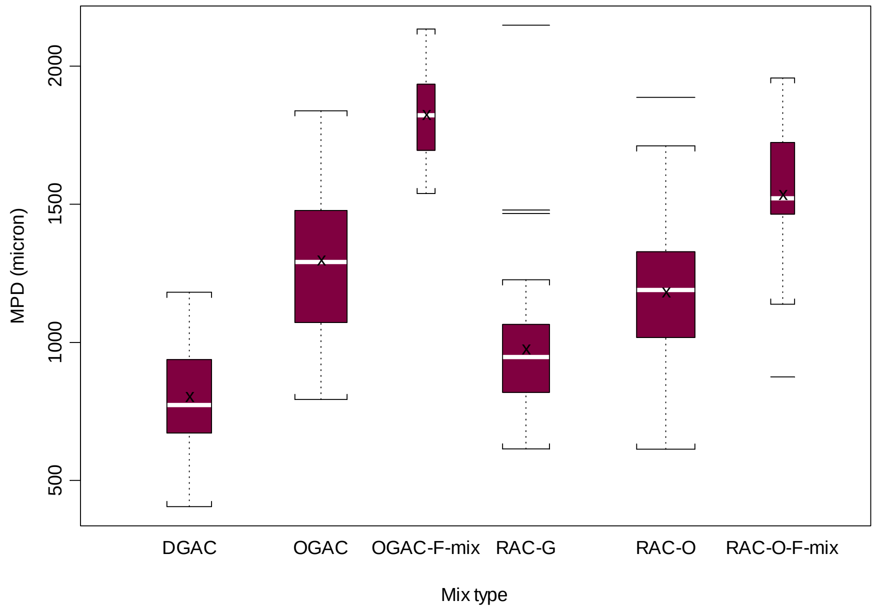


Figure A.5: Variation in MPD values for different mix types for pooled data for all five years and all initial ages.

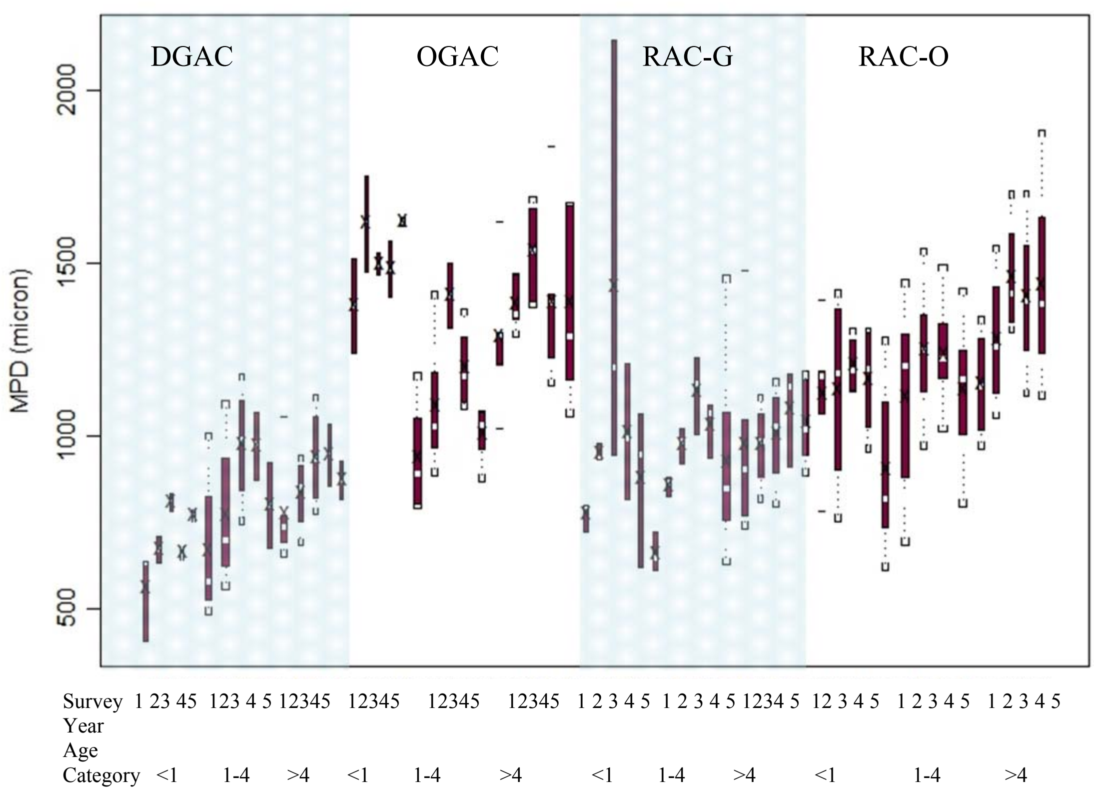


Figure A.6: Comparison of MPD values for different mix types for different initial age categories (Age Category) and for five years of data collection.

Table A.7: Regression Analysis of Single-Variable Models for MPD

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	**Age (years)**	3.08E+01	0.000	900.878	0.110
2	**Air-void Content (%)**	3.76E+01	0.000	568.286	0.440
3	**Mix Type**	4.74E+02	0.000	783.109	0.400
4	**Rubber Inclusion**	7.31E+01	0.048	1028.788	0.016
5	**Fineness Modulus**	3.82E+02	0.000	-822.263	0.366
6	**NMAS (mm)**	-4.02E+01	0.000	1585.027	0.108
7	**Cu**	-1.07E+01	0.000	1300.270	0.337
8	Cc	4.80E+00	0.616	1061.183	0.001
9	**Surface Thickness (mm)**	-6.08E+00	0.000	1315.142	0.158
10	**IRI (m/km)**	5.97E+01	0.045	977.201	0.017
11	Average Annual Rainfall (mm)	2.54E-03	0.948	1066.997	0.000
12	Average Annual Wet Days	5.14E-01	0.182	1031.760	0.007
13	Average Annual Maximum Daily Air Temp (C)	-2.15E+00	0.770	1118.250	0.000
14	Annual Number of Days > 30C	-4.96E-01	0.170	1108.245	0.008
15	Annual Degree-Days > 30C	-1.33E-02	0.192	1105.094	0.007
16	Annual FT Cycles	5.02E-01	0.712	1061.520	0.001
17	Annual AADTT per Coring Lane	1.36E-02	0.238	1051.329	0.006

The results in Table A.7 show that MPD tends to be significantly affected by the age and mix property variables, including air-void content, fineness modulus, nominal maximum aggregate size (NMAS), and aggregate coefficient of uniformity (C_u). According to the estimated coefficients, increasing air-void content and fineness modulus increase macrotexture, and increasing NMAS and C_u reduces macrotexture. A decrease of macrotexture with an increase of NMAS is unexpected. This is likely due to the pooling of dense- and open-graded mixes and the effect of other uncontrolled factors in the single-variable model. Also, macrotexture seems to be smaller on thicker surface layers, probably due to better compaction of thicker layers. Rubberized mixes seem to have higher MPD values, likely because of the gap- and open-gradations of the rubberized mixes, while the nonrubberized mixes included a dense gradation. Higher temperature (in terms of both maximum daily air temperature and the number of days with air temperature greater than 30ºC) tends to reduce macrotexture but the effect of air temperature is not significant. Heavier daily traffic volume tends to increase macrotexture, which is most likely due to removal of fines around the larger stones in the surface, resulting in raveling. The effect of traffic is also not statistically significant.

Based on the results in Table A.7, multiple regression analysis was conducted to account for the effect of various factors simultaneously. Highly correlated independent variables are mutually excluded from the modeling. Two separate regression models were proposed to determine the effects of mix type and mix properties on MPD. 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 a finding of an insignificant effect for these two factors.

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

$$\begin{aligned}MPD(micron) &= 825.4166 + 16.8619\times Age(year) - 107.3078\times ind(MixTypeOGAC) + 191.9731\times ind(MixTypeRAC-G)\\&+330.3054\times ind(MixTypeRAC-O) - 7.8439\times NMAS(mm) + 0.0574\times Thickness(mm) - 0.4707\times NumberOfDays > 30C\\&+0.009\times AADTTinCoringLane + 50..1881\times Age\times ind(MixTypeOGAC) - 1.0552\times Age\times ind(MixTypeRAC-G)\\&+12.356\times Age\times ind(MixTypeRAC-O)\end{aligned} \quad \textbf{(A.3.1)}$$

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.8: Regression Analysis of Multiple-Variable Models for MPD for All Mix Types

	Value	Std. Error	t value	P-value
(Intercept)	825.4166	129.3363	6.3819	0
Age	16.8619	7.927	2.1272	0.0345
MixTypeOGAC	107.3078	109.0907	0.9837	0.3263
MixTypeRAC-G	191.9731	76.8337	2.4986	0.0132
MixTypeRAC-O	330.3054	73.9467	4.4668	0
NMAS	-7.8439	6.6905	-1.1724	0.2423
Thickness	0.0574	0.9029	0.0636	0.9493
NoDaysTempGT30	-0.4707	0.2745	-1.7149	0.0877
AADTTCoringLane	0.009	0.0088	1.0227	0.3075
AgeMixTypeOGAC	50.1881	15.8335	3.1697	0.0017
AgeMixTypeRAC-G	-1.0552	12.2535	-0.0861	0.9314
AgeMixTypeRAC-O	12.356	10.9494	1.1285	0.2603

Residual standard error: 201.8 on 229 degrees of freedom; Multiple R-Squared: 0.52.

The R^2 value is relatively low 0.52 but indicates some ability of the combined mix type model to explain MPD. It can be seen that at the 95 percent confidence level, age and mix type significantly affect macrotexture. Among the three pavement types, OGAC, RAC-G, and RAC-O, all have higher initial MPD than DGAC, but OGAC is statistically insignificantly different from DGAC. This is likely due to the removal of the two newly paved OGAC pavement sections from the analysis. P-values for the interaction terms between age and mix type showed that the growth rate (with age) of MPD of OGAC pavements is significantly higher than that of DGAC pavements. The growth rates of MPD of RAC-G and RAC-O pavements are not statistically different from those of DGAC pavements.

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

For DGAC pavements:

$$MPD(micron) = -330.3519 - 3.0386 \times AirVoid(\%) + 21.4366 \times Age(year) + 363.1114 \times FinenessModulus$$
$$-26.4093 \times NMAS(mm) - 3.0755 \times Thickness(mm) - 0.0558 \times NumberOfDays > 30C \quad \textbf{(A.3.2)}$$
$$-0.0174 \times AADTTinCoringLane$$

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

	Value	Std. Error	t value	P-value
(Intercept)	-330.3519	537.856	-0.6142	0.5464
AirVoid	-3.0386	20.4435	-0.1486	0.8834
Age	21.4366	8.4419	2.5393	0.02
FinenessModulus	363.1114	159.9048	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:

$$MPD(micron) = -546.9092 + 17.4418 \times AirVoid(\%) + 80.515 \times Age(year) + 115.8593 \times FinenessModulus$$
$$+30.6636 \times NMAS(mm) + 2.0974 \times Thickness(mm) - 0.0117 \times NumberOfDays > 30C \quad \textbf{(A.3.3)}$$
$$-0.0182 \times AADTTinCoringLane$$

Table A.10: Regression Analysis of Multiple-Variable Models for MPD for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	-546.9092	581.496	-0.9405	0.3572
AirVoid	17.4418	14.9262	1.1685	0.2551
Age	80.515	13.9141	5.7866	0
FinenessModulus	115.8593	137.6151	0.8419	0.4089
NMAS	30.6636	23.2837	1.317	0.2014
Thickness	2.0974	2.0867	1.0051	0.3258
NoDaysTempGT30	-0.0117	0.5084	-0.0229	0.9819
AADTTCoringLane	-0.0182	0.0305	-0.596	0.5572

Residual standard error: 110.9 on 22 degrees of freedom; Multiple R-Squared: 0.8032.

For RAC-G pavements:

$$MPD(micron) = -685.0893 + 4.4461 \times AirVoid(\%) + 50.4253 \times Age(year) + 288.948 \times FinenessModulus$$
$$-18.1208 \times NMAS(mm) + 0.7182 \times Thickness(mm) + 1.8836 \times NumberOfDays > 30C \quad \textbf{(A.3.4)}$$
$$-0.0453 \times AADTTinCoringLane$$

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

	Value	Std. Error	t value	P-value
(Intercept)	-685.0893	1453.188	-0.4714	0.643
AirVoid	4.4461	29.3425	0.1515	0.8812
Age	50.4253	20.5533	2.4534	0.0246
FinenessModulus	288.948	312.587	0.9244	0.3675
NMAS	-18.1208	27.375	-0.6619	0.5164
Thickness	0.7182	4.033	0.1781	0.8606
NoDaysTempGT30	1.8836	1.0179	1.8505	0.0807
AADTTCoringLane	-0.0453	0.0505	-0.8969	0.3816

Residual standard error: 215.1 on 18 degrees of freedom; Multiple R-Squared: 0.3389.

For RAC-O pavements:

$$MPD(micron) = 982.5441 + 5.8459 \times AirVoid(\%) + 21.0669 \times Age(year) + 289.865 \times FinenessModulus$$
$$-137.6562 \times NMAS(mm) + 7.5815 \times Thickness(mm) - 1.0076 \times NumberOfDays > 30C \qquad \textbf{(A.3.5)}$$
$$-0.0078 \times AADTTinCoringLane$$

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

	Value	Std. Error	t value	P-value
(Intercept)	982.5441	927.4074	1.0595	0.2965
AirVoid	5.8459	14.5282	0.4024	0.6898
Age	21.0669	9.2168	2.2857	0.0283
FinenessModulus	289.865	208.2709	1.3918	0.1725
NMAS	-137.6562	29.0949	-4.7313	0
Thickness	7.5815	3.1198	2.4301	0.0202
NoDaysTempGT30	-1.0076	0.5797	-1.7381	0.0907
AADTTCoringLane	-0.0078	0.0145	-0.5366	0.5948

Residual standard error: 146.5 on 36 degrees of freedom; Multiple R-Squared: 0.6787.

The R^2 for the RAC-G model is extremely low, probably because the RAC-G mixes show little change in macrotexture over the ages included in this study. This indicates that the RAC-G mixes show little tendency to ravel. The R^2 of the models for the other three mixes are all above 0.50, and for OGAC it is 0.80. The OGAC mixes show the greatest change in macrotexture over the ages included in this study, indicating that it has the highest propensity to ravel over time. The results show that within each mix type, air-void content does not have a significant effect on the value of MPD. Fineness modulus is significant in affecting the macrotexture of dense-graded pavements and is insignificant for RAC-G, OGAC, and RAC-O pavements. Generally, macrotexture increases with fineness modulus, with increasing fineness modulus indicating a coarser gradation. Layer thickness is significant on RAC-O pavements. The effect of pavement age on macrotexture is statistically significant for all four mix types, and more significant (in terms of practical significance) on nonrubberized open-graded pavements (OGAC) than on rubberized open-graded pavements (RAC-O).

A.3.3: Summary of Findings

The following findings were obtained regarding macrotexture:

1. Among all the mixes investigated, F-mixes have the highest MPD. RAC-G mixes have higher MPD values than dense-graded mixes, while open-graded mixes have higher MPD values than RAC-G mixes. Between the two open-graded mixes, the OGAC mixes have higher MPD values than the RAC-O mixes.
2. The R^2 for the RAC-G model is extremely low, probably because the RAC-G mixes show little change in macrotexture over the ages included in this study, indicating that they have not exhibited raveling. The R^2 of the models for the other three mixes are all above 0.50, and for OGAC it is 0.80. The OGAC mix shows the greatest change in macrotexture over the ages included in this study, indicating that it has the highest propensity to ravel over time.
3. MPD generally increases with pavement age. For open-graded mixes, the age effect on macrotexture is more prominent on nonrubberized pavements (OGAC) than on rubberized pavements (RAC-O). The growth rate (with age) of MPD is significantly higher on OGAC pavements than on DGAC, RAC-G, and RAC-O pavements. The growth rates of MPD of RAC-G and RAC-O pavements are not statistically different from those of DGAC pavements.
4. Within each mix type, air-void content does not have a significant effect on the value of MPD.
5. Fineness modulus is significant in affecting the macrotexture of dense-graded pavements, and is insignificant for RAC-O, RAC-G, and OGAC pavements.
6. Layer thickness is only significant on RAC-O pavements. Thicker RAC-O layers have higher macrotexture.
7. Mixes containing rubber have higher MPD values, most likely because the rubberized mixes include gap- and open-gradations, while the nonrubberized mixes include dense-gradations.

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 chapter first focuses on the 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 different ranges of frequency of OBSI?

It is generally considered 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). The 800 and 1,000 Hz frequencies, which often have the highest sound intensity due to the nature of tire/pavement noise and weighting for human perception through the highest values on the A-weighted scale, are generally considered to be predominantly influenced by tire tread size, with some lesser influence from both of the pavement-related mechanisms (air pumping and tire vibration). 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-voids, 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 will be revisited in more detail in this report based on the fifth-year 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, type of test tire, type of sound analyzer, and air density.

The effect of pavement temperature was included as part of this study and addressed in a separate report *(5).* In the analysis of the first four years' results *(1, 3, 6),* the pavement temperature correction was not applied because the calibration equations were unavailable at that time and it was believed that the pavement temperature effect on noise is small. In the fourth and fifth year of this study, the effect of pavement temperature was analyzed explicitly and addressed in a separate report *(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 five years of data 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 the lack of conversion equations. In this report, both the 30-mph and 35-mph measurements were removed from the analysis based on discussions between UCPRC and Caltrans.

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 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 measurements for analysis in the third-year report *(3).* In the fourth-year, data that were collected with the SRTT#2 tire were converted to SRTT#1 data using a set of newly developed correction equations described in Appendix B.2: Development of Calibration Equations for Pavement Temperature, Test Tire, Speed, and Analyzer Equipment.

In this report, the fifth-year data, which were collected with the SRTT#4 tire, are converted to SRTT#1 data by the same equation developed and presented in Appendix B.2: Development of Calibration Equations for Pavement Temperature, Test Tire, Speed, and Analyzer Equipment.

It should be noted that 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, the Larson Davis results were converted to Harmonie results.

As discussed above, several varying factors were involved in the measurement of OBSI over the five years. While calibration equations have been developed and applied for some factors, these equations were typically developed under certain specific conditions without consideration of the interactions between factors. To improve the calibration equations for a broader range, two factorial experiments were conducted in the field in mid-2010 using the Aquatred 3 #3 tire and the SRTT#3 and SRTT#4 tires, and from these experiments comprehensive correction equations were developed for the SRTT#3 and SRTT#4 tires. Significant differences between the different SRTT tires were then detected when the new correction equations were applied to the fifth-year data. Consequently, several additional experiments were conducted using four SRTT tires (SRTT#1, SRTT#2, SRTT#3, and SRTT#4) on both asphalt pavements and concrete pavements to develop the calibration equations among SRTT tires. A summary of the experiments and results is included in Appendix B.2.

After all the sound intensity measurements were calibrated to their equivalent values at reference conditions (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 the differences caused by variations of air density (a function of air temperature, humidity, and altitude) *(1).*

A.4.2: Evaluation of Overall Sound Intensity

The overall A-weighted sound intensity levels are calculated by summing 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, dB(A). The frequencies included in the analysis in this study are 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 converted to SRTT#1.

A.4.2.1: Descriptive Analysis

It can be seen from Figure 4.2 that the OBSI values in the fifth survey year were generally higher than those in the fourth survey year. Also, the OBSI time trends on the various surface mixes were the same as those observed in the four-year data analysis: the overall noise level generally increased with pavement age. 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. RAC-O had the lowest overall noise level. After the pavements were exposed to traffic, the overall sound intensity measured on RAC-G pavements quickly approached the representative value measured on DGAC pavements of similar ages. This was previously found to be attributable to a large decrease in air-void content for RAC-G mixes between construction and two years after construction that was due to generally poor compaction during construction *(1).* The overall sound intensity measured on the OGAC pavements appears to remain stable for about six years and then increases quickly with pavement age and reaches a terminal value. With a few exceptions, the overall sound intensity measured on the RAC-O pavements appears to remain stable for about seven years and then increases quickly with pavement age. No terminal limit was observed for RAC-O mix. Based on these observations, the rank of the four mix types (from best to worst) in terms of noise is RAC-O, OGAC, RAC-G, and DGAC.

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 include: 01-N114 (DGAC), QP-20 (OGAC), 01-N105 (OGAC), QP-42 (RAC-O), and 06-N466 (RAC-O).

The overall OBSI value measured on Section 01-N114 in the third survey year was about 2 dB(A) lower than the value measured in the second survey year. The reason for the drop is unclear. It is possibly due to the combined effect of variations in pavement temperature (the measurement was taken in August in the second year and in May in the third year), use of different test tires (Aquatred 3 tire in the second year versus SRTT 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 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 five years for different mix types for the three original age categories. As the figure shows, overall sound intensity generally increases with pavement age for the same pavement section. Overall, the increased rate of sound intensity is the lowest on RAC-O pavements, which means that RAC-O pavements remain quieter than DGAC pavements longer than do OGAC pavements. As pointed out in the three-year data analysis report *(3),* "Quieter" or "Noise reduction" is defined for this study as the difference between the tire/pavement noise of each mix type other than DGAC compared to the average noise level of DGAC with the same ages.

Figure A.7 shows the estimated cumulative distribution function (CDF) of noise reduction for both the OGAC and RAC-O types of open-graded mixes and RAC-G mixes compared to the average noise levels of 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 smooths the curves. The numbers in parentheses in the legends represent the sample size of each mix type. All five years of observations were aggregated to create the plots. As can be seen, the sample sizes are different among the different mixes and age groups. The average noise level of DGAC mixes in each age group, as shown in the legend, is 101.3 dB(A) for newly paved overlays, 102.0 dB(A) for pavements between one and three years old, and varies between 103.3 and 103.9 dB(A) for pavements older than three years.

A positive value in Figure A.7 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 noise change is generally between a 3 dB(A) increase and a 7 dB(A) reduction.

For newly paved overlays (age less than or equal to one year), RAC-G and RAC-O pavements seem to be quieter than OGAC pavements. If at least a 3 dB(A) noise reduction is required for a surface to be considered noise-reducing, only 10 percent of RAC-G and RAC-O pavements are noise-reducing and, based on a small sample size, OGAC pavements are not noise reducing compared to DGAC pavements of the same ages.

For pavements with an age between one and three years, OGAC and RAC-O pavements have similar noise-reducing ability (about 25 percent of pavements are at least 3 dB[A] quieter than average DGAC pavement of the same ages), while at this age RAC-G pavements begin to lose their noise-reducing properties.

For pavements with an age between three and five years, OGAC and RAC-O pavements have similar noise-reducing ability, which is better than that of RAC-G pavements. About 50 percent of RAC-O and OGAC pavements and 15 percent of RAC-G pavements in this age range are at least 3 dB(A) quieter than the average DGAC pavement within the same age range. The reason for the increased percentage of noise-reducing pavements is that the referenced DGAC pavements become much noisier with age (103.3 dB[A] in the three-to-five year age range versus 101.3 dB[A] at less than one year).

For pavements with an age between five and seven years, RAC-O pavements have a noise-reducing ability superior to both RAC-G and OGAC. For pavements with an age between seven and nine years, RAC-O seems to be the only option that can still reduce noise levels by at least 3 dB(A) compared with DGAC of the same age range.

For pavements that are older than nine years, no mix type can be used to achieve the 3 dB(A) noise-reducing effect. Interestingly, OGAC pavements with age older than nine years old seem to be noisier than DGAC pavements.

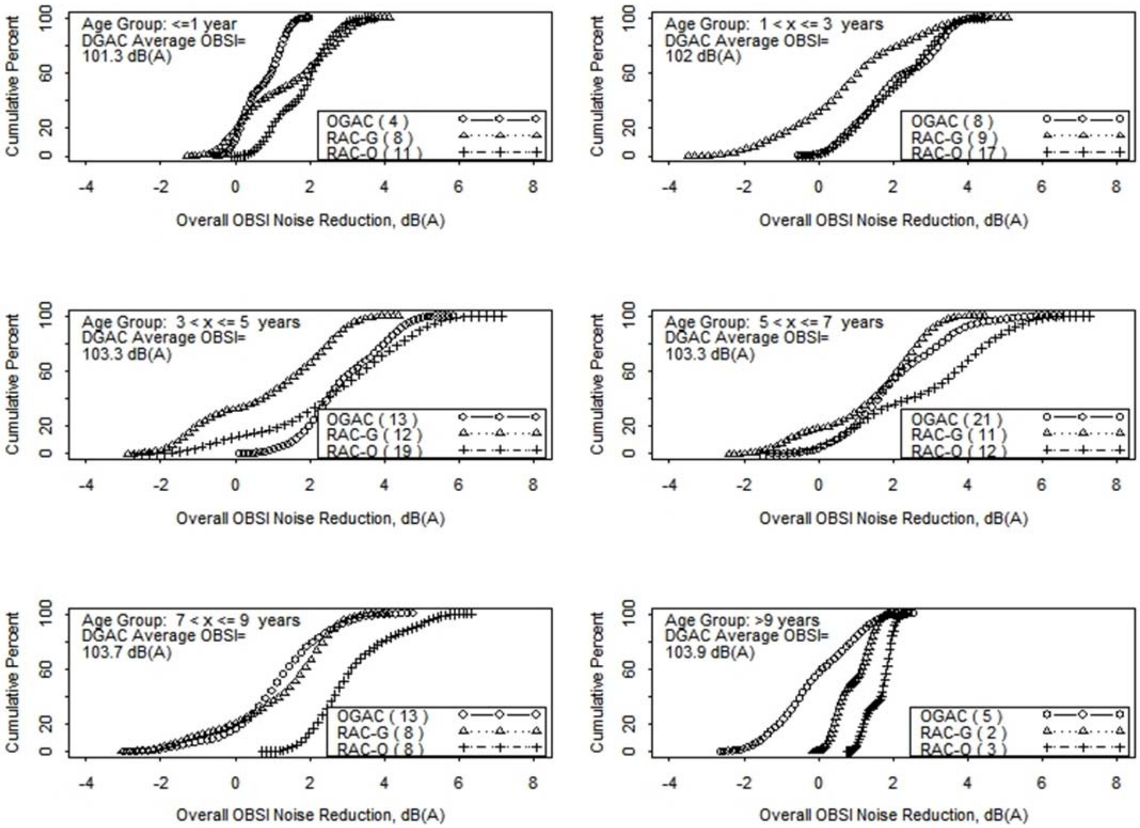


Figure A.7: Estimated cumulative distribution functions of noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

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 should be included in the noise prediction models. Both variables were measured in the first two-year survey *(1),* but not in the third year and fifth year *(36).* In the fourth year, about half of the pavement sections were measured for air-void content and in-situ permeability. 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 decrease linearly with time for all mixes. Based on these observations, the missing third-year and fifth-year data were estimated by linear extrapolation or simple linear regression from the available two-year or three-year data.

Multiple linear regression analysis was conducted to determine the effects of various 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 excluded from the data set used for this statistical analysis because they were either outliers or contained erroneous measurements in one year.

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

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

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

	Value	Std. Error	t value	P-value
(Intercept)	101.9578	0.5823	175.0806	0
Age	0.197	0.0522	3.7744	0.0002
PvmntTypeOGAC	-3.7164	0.5239	-7.093	0
PvmntTypeRAC-G	-1.6492	0.4709	-3.5021	0.0006
PvmntTypeRAC-O	-3.0032	0.4669	-6.4322	0
Thickness	-0.0185	0.0056	-3.2906	0.0012
NoDaysTempGT30	0.0072	0.0019	3.7893	0.0002
AADTperLane	0	0	1.1678	0.2441
MPD	0.0003	0.0003	0.8701	0.3852
AgePvmntTypeOGAC	0.2336	0.0775	3.0156	0.0029
AgePvmntTypeRAC-G	0.0617	0.0773	0.7985	0.4254
AgePvmntTypeRAC-O	-0.0375	0.0741	-0.5061	0.6133

Residual standard error: 1.268 on 233 degrees of freedom; Multiple R-Squared: 0.54

The R^2 shows that the model explains approximately 54 percent of the variation in the dependent variable. The estimation results are very similar to the results based on the first four years of data *(3, 6),* only with slight changes in the values of estimated parameters. Specifically, at the 95 percent confidence level, age, mix type, and surface layer thickness significantly affect the overall sound intensity. All three surface mix types, OGAC, RAC-G, and RAC-O, have lower initial overall sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes were about 3.7, 1.6, and 3.0 dB(A), respectively

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

For DGAC pavements

$$\begin{aligned} &Overall\ Sound\ Intensity(dBA){=}102.055\text{-}0.182\times\log(Permeability)(cm/\sec)+0.0185\times Age(year)-1.1368\times FinenessModulus \\ &+0.0038\times MPD-0.0035\times Thickness(mm)+0.0034\times NumberOfDays>30C+0.0001\times AADTTinCoringLane \end{aligned} \quad \textbf{(A.5.3)}$$

Table A.14: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	102.055	3.5611	28.6586	0
log(Permeability)	-0.182	0.1365	-1.3327	0.1992
Age	0.0185	0.0529	0.35	0.7304
FinenessModulus	-1.1368	0.7732	-1.4703	0.1587
MPD	0.0038	0.0013	2.9952	0.0078
Thickness	-0.0035	0.0086	-0.4032	0.6915
NoDaysTempGT30	0.0034	0.0038	0.912	0.3738
AADTTCoringLane	0.0001	0	2.2542	0.0369

Residual standard error: 0.7403on 18 degrees of freedom; Multiple R-Squared: 0.69.

For OGAC pavements

$$\begin{aligned} &Overall\ Sound\ Intensity(dBA){=}100.4206\text{-}0.0951\times\log(permeability)(cm/\sec)+0.3598\times Age(year)-0.884\times FinenessModulus \\ &+0.0007\times MPD(micron)-0.0029\times Thickness(mm)+0.0068\times NumberOfDays>30C+0.0001\times AADTTinCoringLane \end{aligned} \quad \textbf{(A.5.4)}$$

Table A.15: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	100.4206	3.7119	27.0533	0
log(Permeability)	-0.0951	0.1137	-0.8369	0.4095
Age	0.3598	0.0718	5.0122	0
FinenessModulus	-0.884	0.6344	-1.3934	0.1741
MPD	0.0007	0.0008	0.9045	0.3732
Thickness	-0.0029	0.0114	-0.255	0.8005
NoDaysTempGT30	0.0068	0.0038	1.7748	0.0864
AADTTCoringLane	0.0001	0	4.4283	0.0001

Residual standard error: 0.8233 on 29 degrees of freedom; Multiple R-Squared: 0.77**.**

For RAC-G pavements

$$Overall\ Sound\ Intensity(dBA) = 97.2109 - 0.3672 \times \log(permeability)(cm/\sec) + 0.1289 \times Age(year) - 0.4193 \times FinenessModulus + 0.0026 \times MPD(micron) + 0.0033 \times Thickness(mm) + 0.0088 \times NumberOfDays > 30C \quad \textbf{(A.5.5)}$$

Table A.16: Regression Analysis of Multiple-Variable Models for Overall Sound Intensity for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	97.2109	4.9448	19.6591	0
log(Permeability)	-0.3672	0.1078	-3.4066	0.0025
Age	0.1289	0.0823	1.5659	0.1316
FinenessModulus	-0.4193	0.9816	-0.4272	0.6734
MPD	0.0026	0.0009	2.9633	0.0072
Thickness	0.0033	0.0125	0.2664	0.7924
NoDaysTempGT30	0.0088	0.0035	2.4939	0.0206
AADTTCoringLane	0	0	0.678	0.5048

Residual standard error: 0.8825 on 22 degrees of freedom; Multiple R-Squared: 0.75.

For RAC-O pavements

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

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

	Value	Std. Error	t value	P-value
(Intercept)	114.3716	7.2568	15.7606	0
log(Permeability)	0.3798	0.2664	1.4257	0.1639
Age	0.3337	0.1183	2.8204	0.0083
FinenessModulus	-2.0384	1.2042	-1.6928	0.1005
MPD	-0.0013	0.001	-1.3097	0.1999
Thickness	-0.0772	0.0329	-2.3474	0.0255
NoDaysTempGT30	-0.0001	0.0033	-0.0157	0.9876
AADTperCoringLane	0	0	0.1266	0.9001

Residual standard error: 0.902 on 31 degrees of freedom; Multiple R-Squared: 0.45.

Except for the RAC-O mix model, the R^2 for the individual mix models are all above 0.69 and better than that of the combined model. The results show that overall sound intensity increases with pavement age for all mix types but it is only significant for OGAC and RAC-O mixes. At the 95 percent confidence level, the in-situ permeability is a significant factor for RAC-G. 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 very 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. The harsher surface causes more tire vibration and consequently produces more noise. For OGAC and RAC-O pavements, MPD does not have a significant influence on noise level.

For all 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. For RAC-G mixes, high temperature days (NoDaysTempGT30) is significant, and the estimated coefficient (0.0088) indicates that tire/pavement noise increases when the number of high temperature days increases.

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

Sound intensity was analyzed at each one-third octave frequency band. The frequencies included in the analysis are between 500 and 5,000 Hz, including 500, 630, 800, 1,000, 1,250, 1,600, 2,000, 2,500, 3,150, 4,000, and 5,000 Hz. In this report, detailed statistical analysis was performed for four typical frequency levels: 500, 1,000, 2,000, and 4,000 Hz.

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

<u>A.4.3.1 Change of OBSI Spectra with Age</u>

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

From Figure 4.5, it can be seen that for newly paved overlays, the overall sound intensity changed little in the first five years on both open-graded pavements (OGAC and RAC-O). For DGAC and RAC-G pavements, the overall sound intensity increased slightly in the first two years, increased significantly in the third year, and remained relatively unchanged in the fourth and fifth year. 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. This increase of high-frequency noise indicates that the air-void content (or permeability) of open-graded pavements decreased in the first five years, which is also due to traffic action. For DGAC and RAC-G pavements, the low frequency noise decreased slightly with age in the first five years, while the sound intensities at frequencies over 1,000 Hz (around 2,500 Hz) increased significantly with age. This indicates that the air-void content of DGAC and RAC-G pavements decreased significantly in the first five years due to further compaction of mixes by action of traffic.

Figure 4.6 shows that for pavements with an age between one and four years at the start of the study, the overall sound intensity increased slightly on both open-graded pavements (OGAC and RAC-O), and increased more significantly on the OGAC and RAC-O pavements. This increase in noise level takes place significantly in higher-frequency region another indication that the air-void content decreased significantly. Moreover, for pavements with an initial age between one and four years, sound intensity increased slightly on both open-graded pavements (OGAC and RAC-O) for frequencies above 1,000 Hz. For frequencies below 1,000 Hz, sound intensity increased for RAC-G and DGAC significantly while for other mix types it remained unchanged over five years. Figure 4.7 shows that for the oldest pavements (initial age greater than four years), the overall sound intensity with age for all mix types slightly increased. The increase of sound intensity with age mainly occurred at frequencies between 1,000 Hz and 2,500 Hz on 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 frequency band.

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

Figure A.8 through Figure A.18 show the five-year measurements of sound intensity at each one-third octave frequency band for the four mix types: DGAC, OGAC, RAC-G, and RAC-O. Sound intensity generally increases with pavement age at most frequency levels.

Figure A.8 and Figure A.9 show that at low-frequency levels (500 Hz and 630 Hz) sound intensities measured on OGAC and RAC-O pavements are generally higher than the values measured on DGAC and RAC-G pavements. This is because tire/pavement noise at low frequencies is dominated by tire vibration, which is significantly affected by the macrotexture of pavement surfaces which tends to be greater on open-graded mixes. Figure A.10 shows that at a frequency level of 800 Hz, the sound intensities measured on OGAC, RAC-G, and RAC-O pavements begin to become lower than those measured on DGAC pavements. This trend becomes much clearer at higher frequency levels where the air pumping mechanism would be expected to dominate, as shown in Figure A.11 through Figure A.18. The figures also show that for frequency levels equal to or larger than 1,000 Hz, the sound intensities measured on OGAC and RAC-O pavements are generally lower than those measured on RAC-G pavements. This is primarily because the two open-graded pavements have higher air-void contents than the gap-graded pavements, which can reduce the tire/pavement noise caused by the air-pumping mechanism.

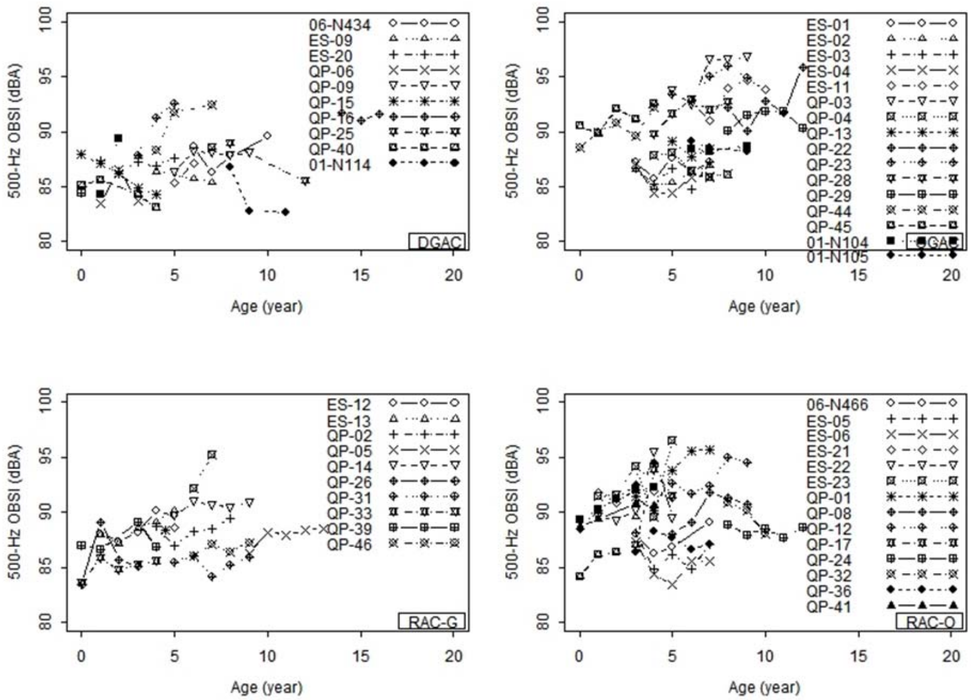


Figure A.8: Sound intensity at 500 Hz over five years for each pavement section.

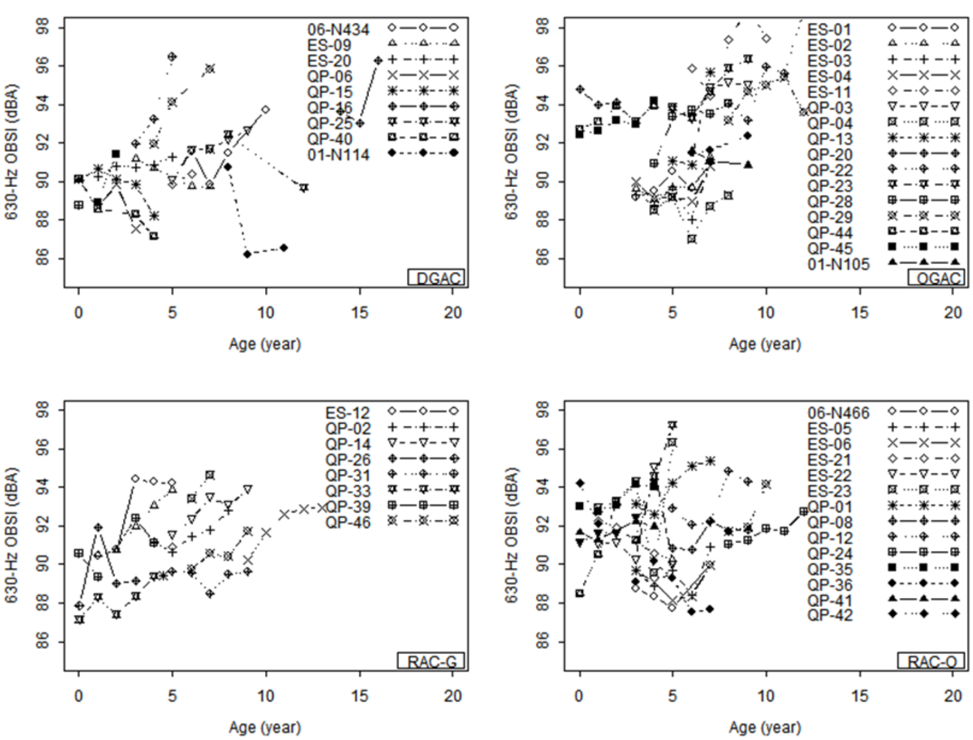


Figure A.9: Sound intensity at 630 Hz over five years for each pavement section.

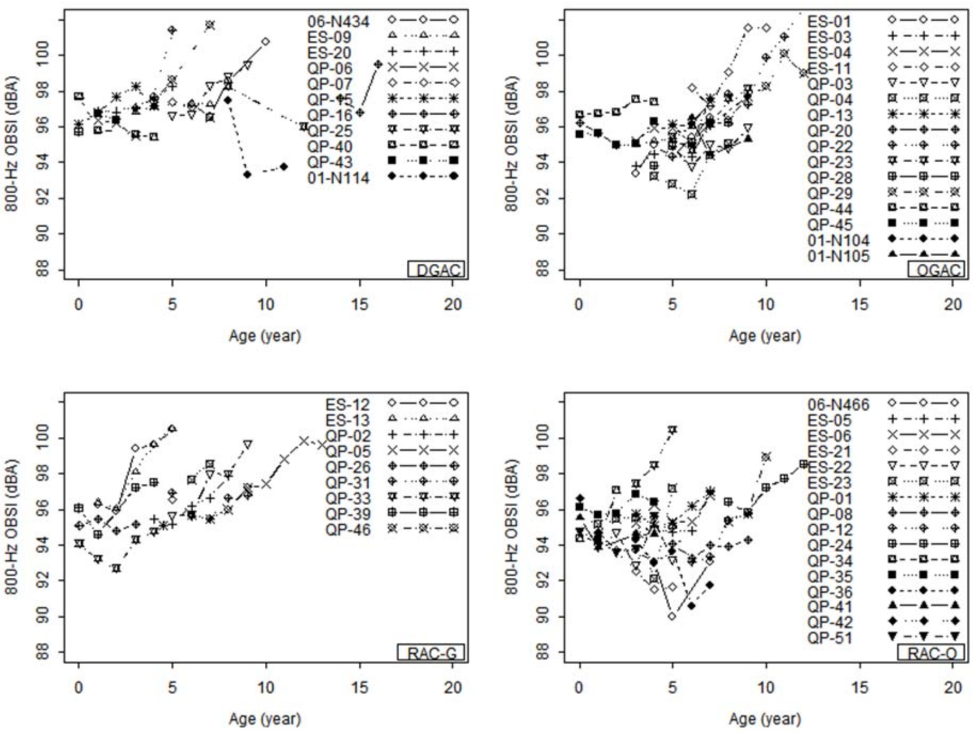


Figure A.10: Sound intensity at 800 Hz over five years for each pavement section.

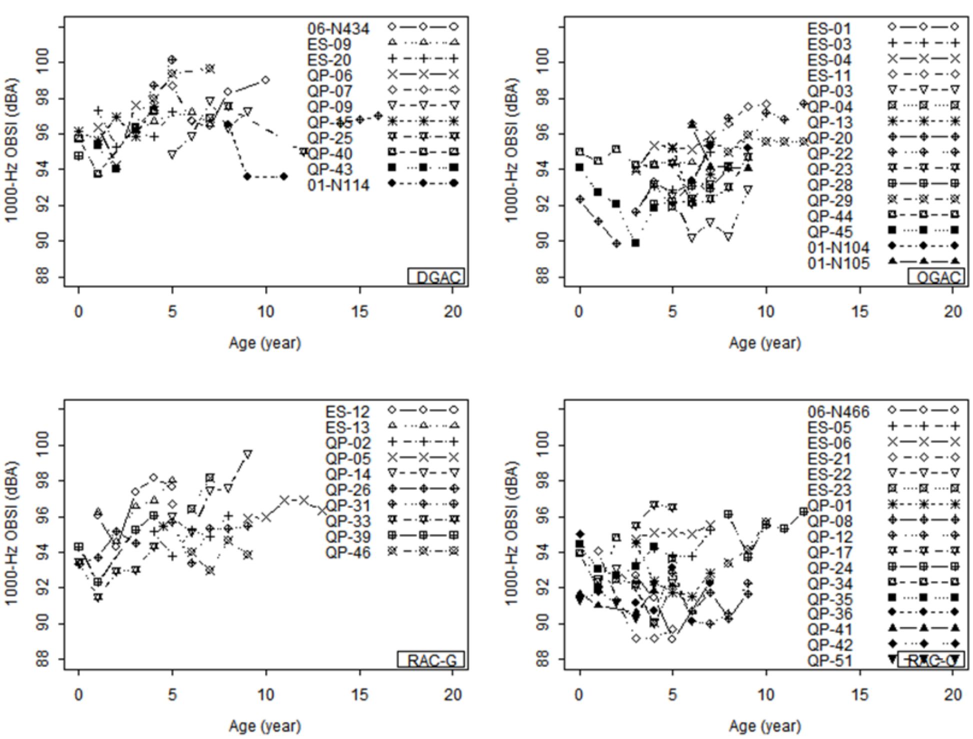


Figure A.11: Sound intensity at 1,000 Hz over five years for each pavement section.

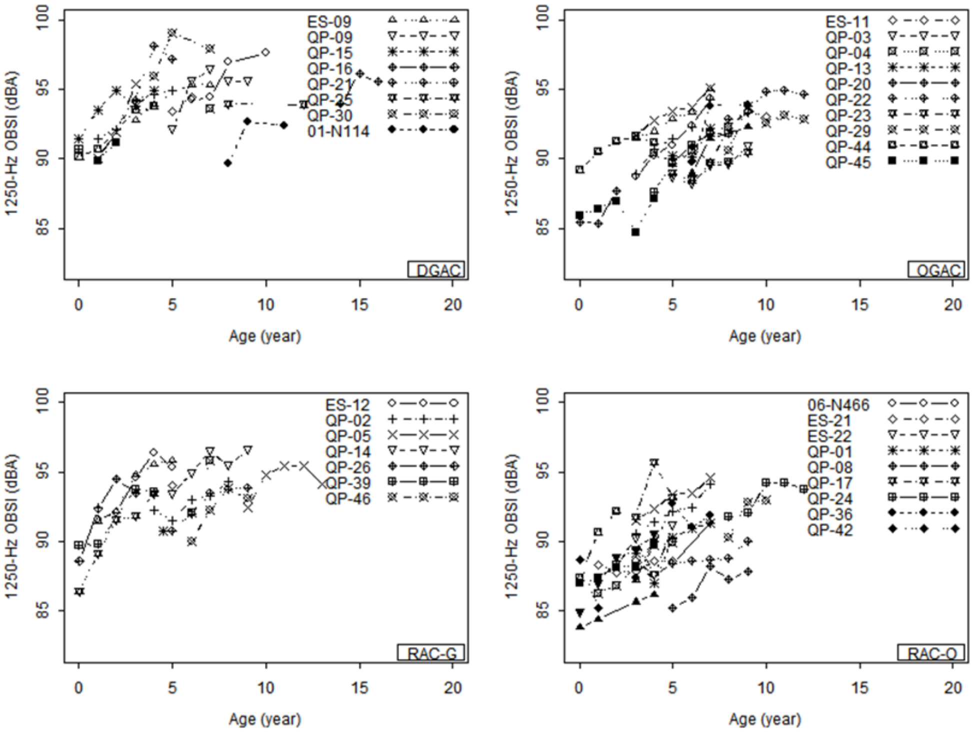


Figure A.12: Sound intensity at 1,250 Hz over five years for each pavement section.

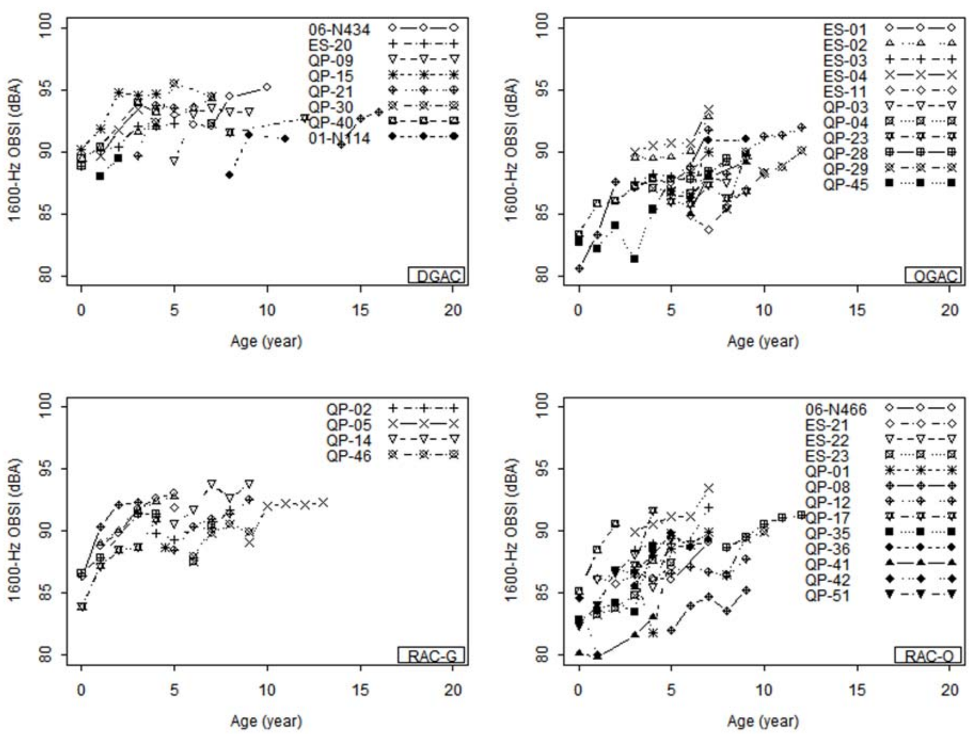


Figure A.13: Sound intensity at 1,600 Hz over five years for each pavement section.

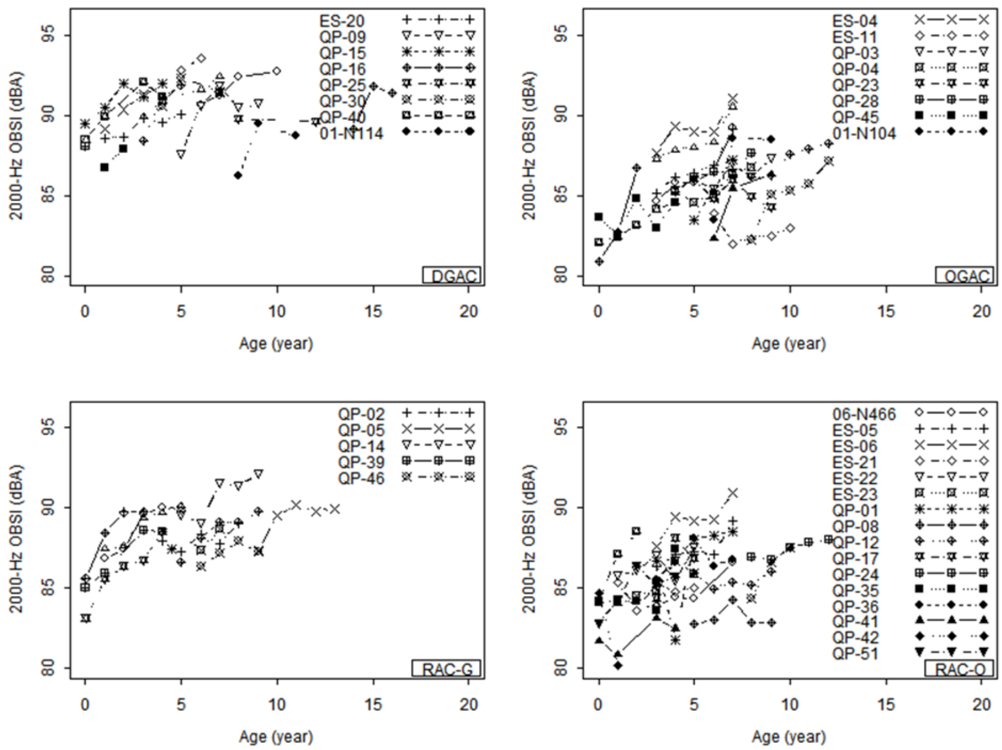


Figure A.14: Sound intensity at 2,000 Hz over five years for each pavement section.

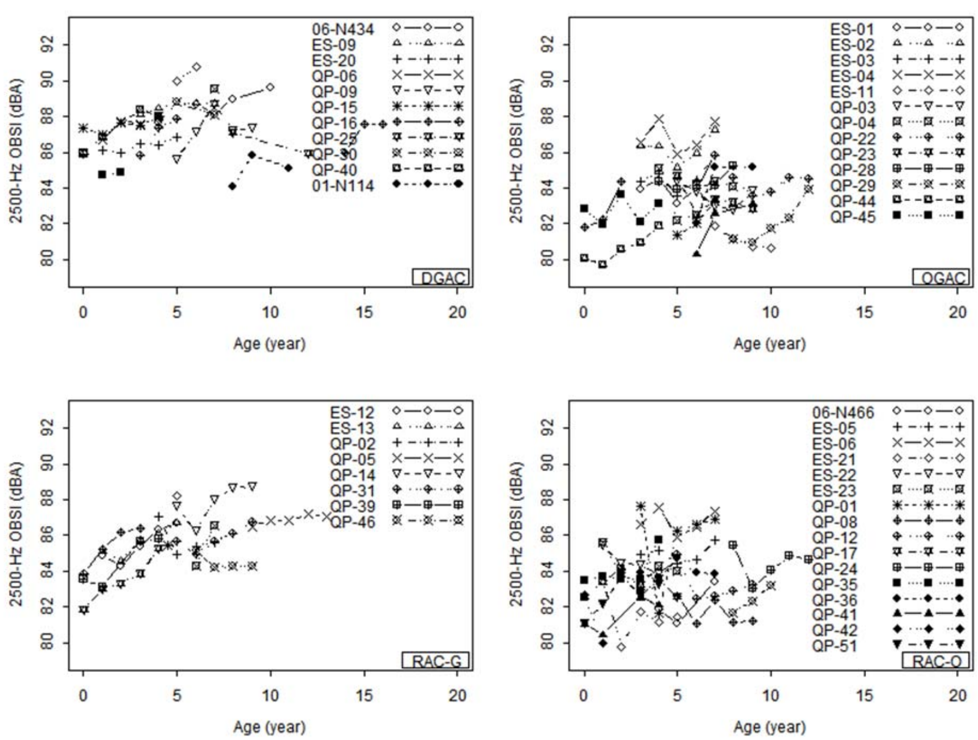


Figure A.15: Sound intensity at 2,500 Hz over five years for each pavement section.

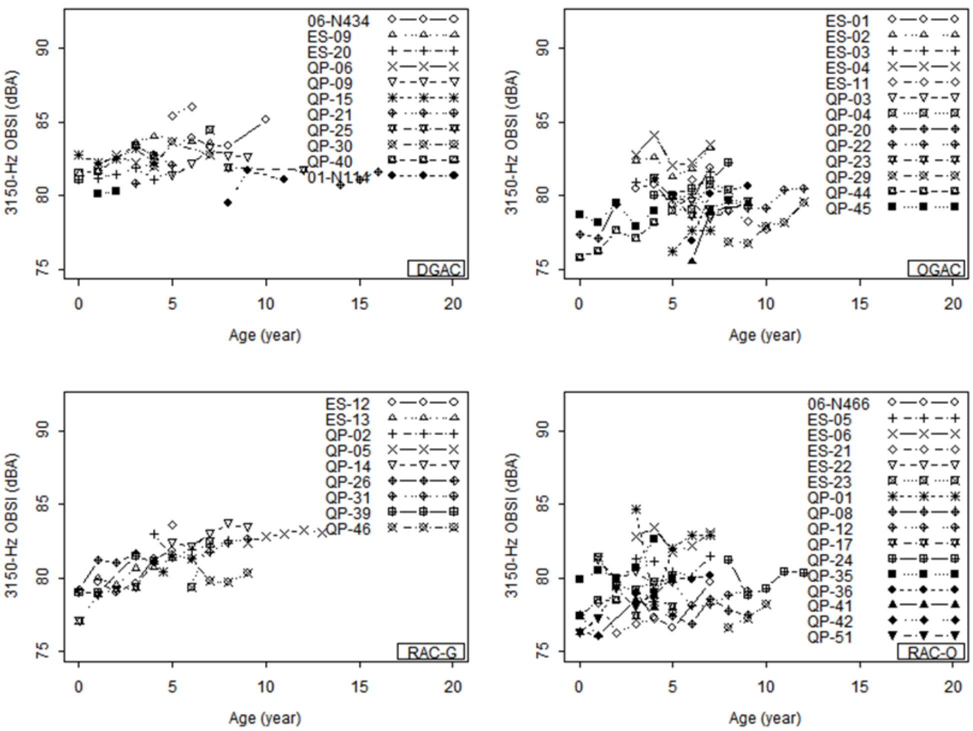


Figure A.16: Sound intensity at 3,150 Hz over five years for each pavement section.

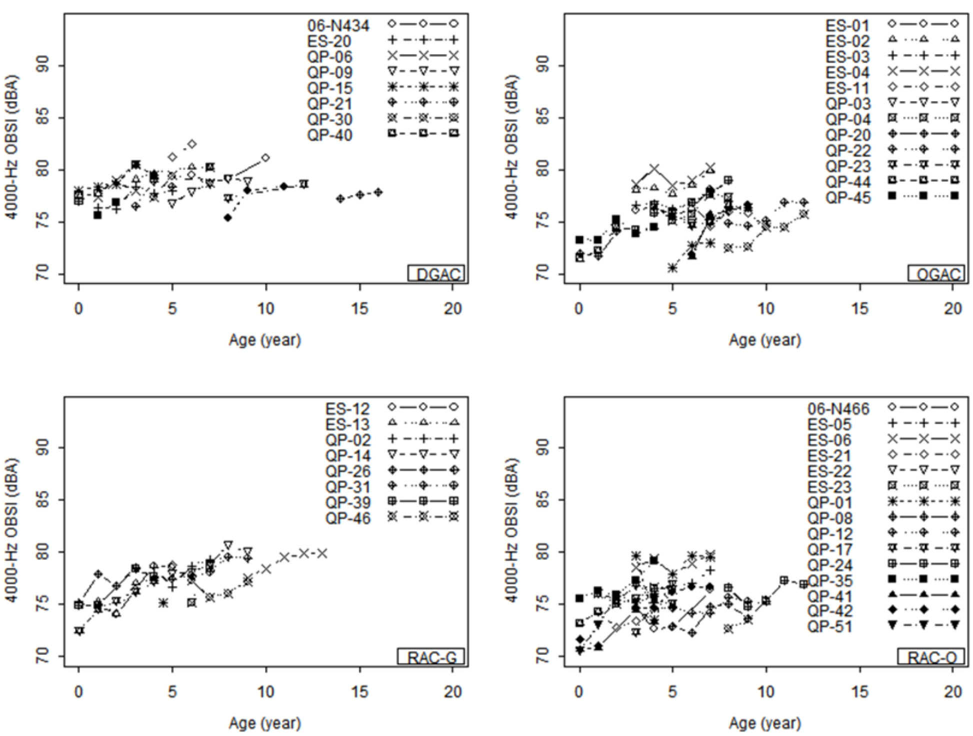


Figure A.17: Sound intensity at 4,000 Hz over five years for each pavement section.

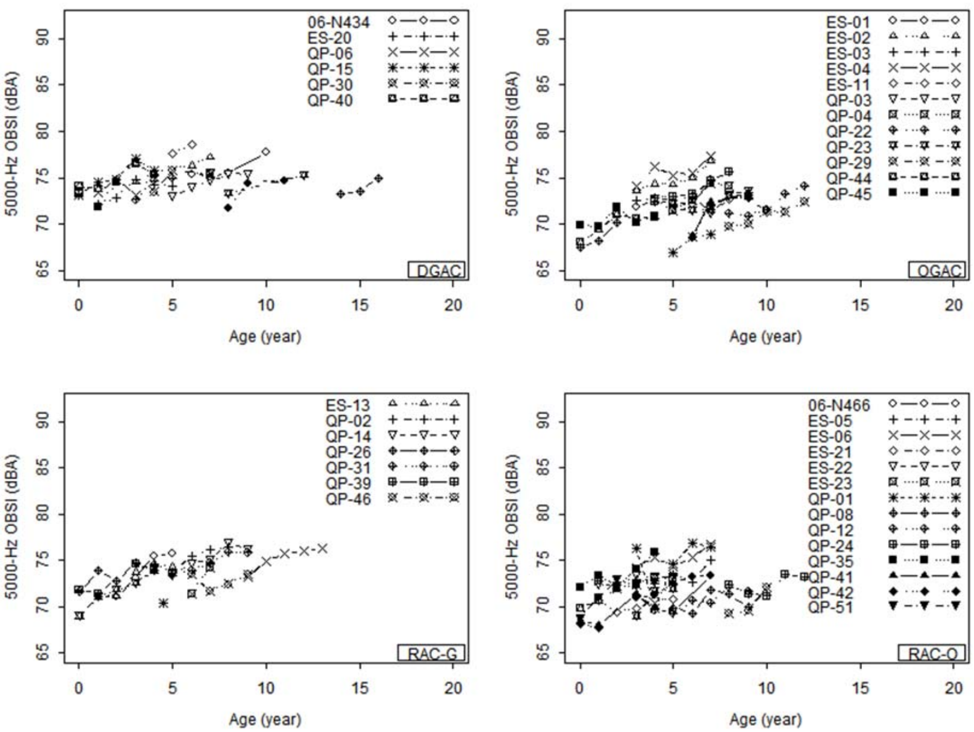


Figure A.18: Sound intensity at 5,000 Hz over five years for each pavement section.

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

A.4.3.3.1 Descriptive Analysis

Figure A.8 shows the 500-Hz OBSI values observed on each pavement section of the four mix types in the five survey years. 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 among the 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. This indicates that OGAC pavements are more prone to raveling and other types of surface distresses that increase the vibration of the tire and leads to a louder noise level at 500 Hz. Variation of 500-Hz sound intensity among the different pavement sections as shown in Figure A.19 seems to be higher for OGAC pavements than for other pavement types. This indicates that different OGAC pavements have significantly different surface textures.

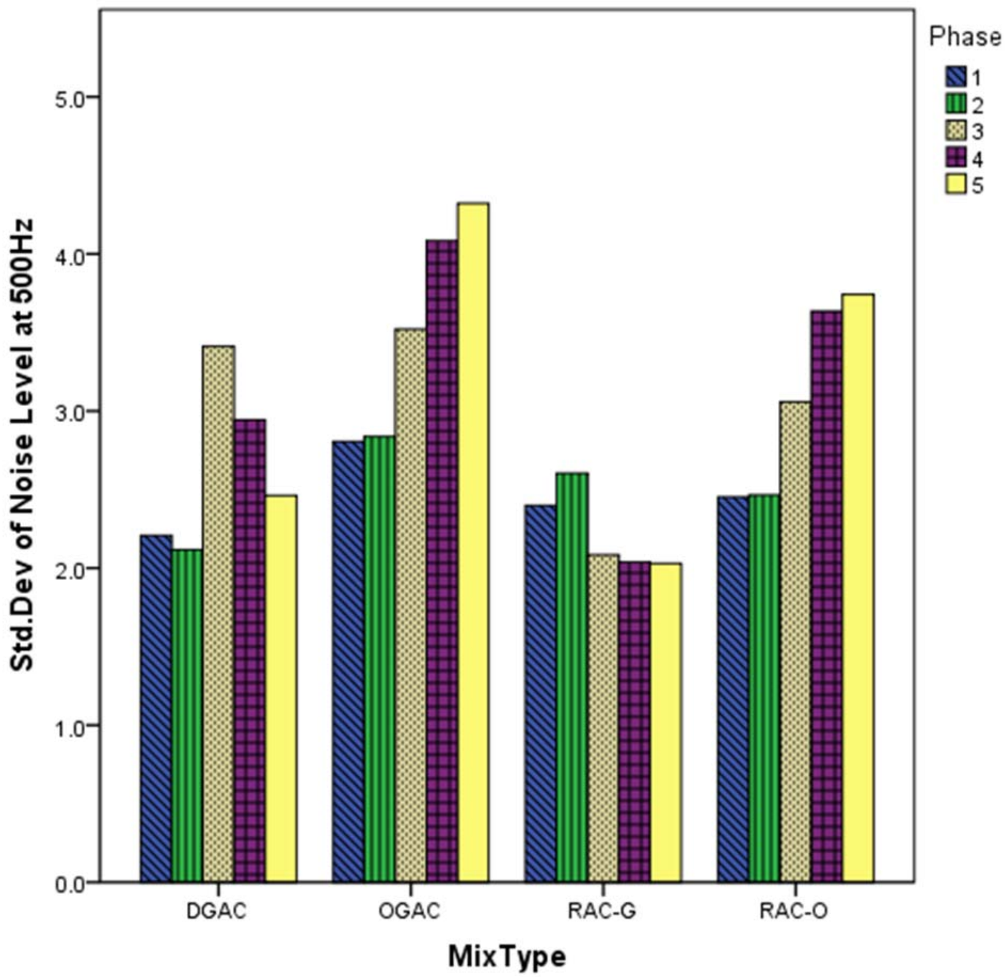


Figure A.19: Standard deviation of sound intensity at 500 Hz for different mix types for five years of data collection.

Figure A.20 shows box plots of the 500-Hz OBSI over five years for different mix types for three age categories. As the figure shows, sound intensity generally increases with pavement age for the same pavement section. Overall, the increase rate of sound intensity is lower on rubberized pavements (RAC-G and RAC-O) than on nonrubberized pavements (DGAC and OGAC).

Figure A.21 shows the estimated cumulative distribution function of 500-Hz noise reduction for both the OGAC and RAC-O types of open-graded mixes and the RAC-G mixes compared to the average 500-Hz noise levels of DGAC mixes in six age groups. The average 500-Hz noise level on DGAC pavements, as shown in the legend, is about 85.7 dB(A) for newly paved overlays, between 86.6 and 88.1 dB(A) for pavements with an age between three and nine years, and approximately 91.0 dB(A) for pavements older than nine years. A negative value in Figure A.21 indicates that the noise level compared to the average DGAC mix noise level has increased. The figure shows that the noise change varies over a wide range for all mixes, from -13 dB(A) to 6 dB(A).

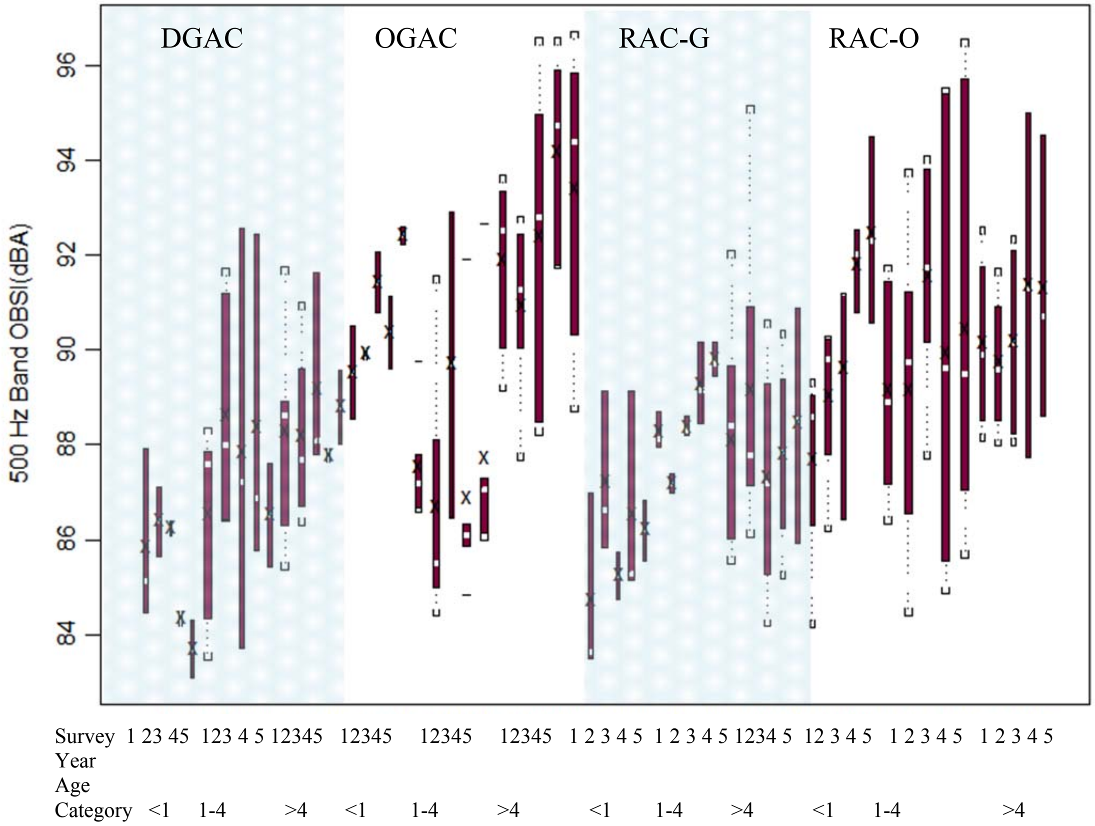


Figure A.20: Sound intensity at 500 Hz for different initial age categories (Age Category) and for five years of data collection.

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. All OGAC pavements and approximately 90 percent of RAC-O pavements are noisier than DGAC pavements.

Among pavements with an age between one and three years, about 10 percent of the RAC-G, 40 percent of the OGAC, and 60 percent of the RAC-O are at least 3 dB(A) noisier than DGAC pavements. No mixes seem to have a noise benefit over DGAC in this age group.

For pavements with an age between four and seven years, RAC-G pavements seem to have similar noise characteristics to those of DGAC mixes. The median of the noise reduction distribution curve is generally around 0 dB(A) for RAC-G and OGAC mixes. RAC-O shows a relatively unsatisfactory noise performance between the ages of three to five years.

For pavements with an age between seven and nine years, both OGAC and RAC-O mixes are noisier than DGAC, while RAC-G is the only option to generally provide noise reduction of 3 dB(A).

For pavements with an age more than nine years, both RAC-G and RAC-O mixes have similar noise characteristics and provide about 3 dB(A) noise reduction over DGAC. OGAC pavements are on average 2 dB(A) noisier than DGAC pavements.

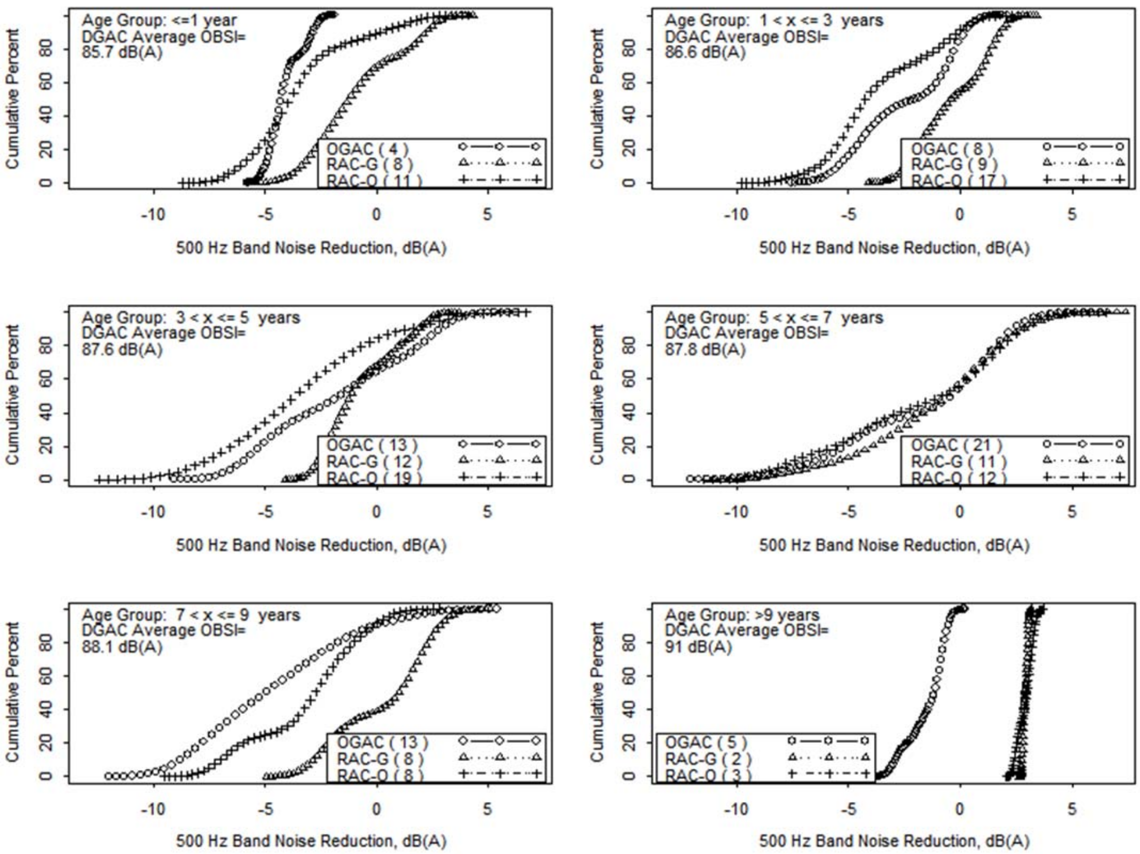


Figure A.21: Estimated cumulative distribution function of 500-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

A.4.3.1.2 Statistical Analysis

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 all variables. Compared to the analysis performed for the four-year report, MPD was used as a surrogate for the surface distresses used in the model (raveling and rutting). 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 are included as the independent variables, and mix property variables are excluded. The regression equation was found to be Equation A.5.7:

$$\begin{aligned} &500Hz\ Sound\ \ Intensity(dBA) = 85.1604 + 0.171 \times Age(year) + 1.0906 \times ind(MixTypeOGAC) - 0.2346 \times ind(MixTypeRAC-G) \\ &+0.5314 \times ind(MixTypeRAC-O) - 0.0115 \times Thickness(mm) - 0.0109 \times NumberOfDays > 30C \\ &+0.0007 \times AADTTinCoringLane + 0.0027 \times MPD \end{aligned} \quad \textbf{(A.5.7)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	85.1604	0.9113	93.4541	0
Age	0.171	0.0525	3.2592	0.0013
PvmntTypeOGAC	1.0906	0.5583	1.9535	0.052
PvmntTypeRAC-G	-0.2346	0.4875	-0.4812	0.6308
PvmntTypeRAC-O	0.5314	0.5454	0.9744	0.3309
Thickness	-0.0115	0.01	-1.1571	0.2485
NoDaysTempGT30	-0.0109	0.003	-3.6868	0.0003
AADTTCoringLane	0.0007	0.0001	6.977	0
MPD	0.0027	0.0006	4.8426	0

Residual standard error: 2.28 on 226 degrees of freedom; Multiple R-Squared: 0.47.

It can be seen that 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. The 500-Hz band noise increases with pavement age, truck traffic volume, and MPD, but decreases with number of high temperature days. High air temperature has a damping effect on the vibration of the tire, and therefore decreases the noise level at 500 Hz. The interaction terms between age and mix type are statistically insignificant, although they are not shown in the model above. This indicates that the growth rate of overall sound intensity is not statistically different among the four pavement types.

In the second set of models, the mix type variable is replaced with mix property variables and the model is estimated for each mix type separately. The regression equations appear as Equation A.5.8 through Equation A.5.11:

For DGAC pavements

$$500Hz\ Sound\ Intensity(dBA) = 84.2628 + 0.4054 \times AirVoid(\%) + 0.1147 \times Age(year) - 0.8866 \times FinenessModulus + 0.005274 \times MPD + 0.0115 \times Thickness(mm) - 0.004897 \times NumberOfDays > 30C - 0.0000313 \times AADTTinCoringLane \quad \textbf{(A.5.8)}$$

Table A.19: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	81.1005	5.4967	14.7544	0
AirVoid	0.4258	0.246	1.731	0.0997
Age	0.1018	0.1175	0.8662	0.3972
FinenessModulus	-0.5755	1.3551	-0.4247	0.6758
MPD	0.0067	0.0024	2.766	0.0123
Thickness	0.0185	0.0204	0.9062	0.3762
NoDaysTempGT30	0.0016	0.0076	0.2133	0.8334
AADTTCoringLane	0	0.0002	-0.1242	0.9024

Residual standard error: 1.532 on 19 degrees of freedom; Multiple R-Squared: 0.65.

For OGAC pavements

$$500Hz\ Sound\ Intensity(dBA) = 97.0369 + 0.5039 \times AirVoid(\%) + 0.2489 \times Age(year) - 2.4513 \times FinenessModulus - 0.002 \times MPD(micron) + 0.0339 \times Thickness(mm) - 0.0349 \times NumberOfDays > 30C + 0.001 \times AADTTinCoringLane \quad \textbf{(A.5.9)}$$

Table A.20: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	97.0369	5.4409	17.8348	0
AirVoid	0.5039	0.1287	3.9154	0.0005
Age	0.2489	0.0943	2.6394	0.0132
FinenessModulus	-2.4513	1.2358	-1.9836	0.0568
MPD	-0.002	0.0013	-1.5491	0.1322
Thickness	0.0339	0.0224	1.5122	0.1413
NoDaysTempGT30	-0.0349	0.0053	-6.5776	0
AADTTCoringLane	0.001	0.0003	3.9804	0.0004

Residual standard error: 1.305 on 29 degrees of freedom; Multiple R-Squared: 0.85.

For RAC-G pavements

$$500Hz\ Sound\ Intensity(dBA) = 83.9685 - 0.2686 \times AirVoid(\%) + 0.0836 \times Age(year) + 0.1831 \times FinenessModulus + 0.0067 \times MPD(micron) - 0.0449 \times Thickness(mm) + 0.0101 \times NumberOfDays > 30C + 0.0006 \times AADTTinCoringLane \quad \textbf{(A.5.10)}$$

Table A.21: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	83.9685	8.1937	10.248	0
AirVoid	-0.2686	0.1823	-1.4732	0.1563
Age	0.0836	0.1351	0.6187	0.5431
FinenessModulus	0.1831	1.7409	0.1052	0.9173
MPD	0.0067	0.0016	4.2371	0.0004
Thickness	-0.0449	0.0261	-1.7215	0.1006
NoDaysTempGT30	0.0101	0.006	1.6961	0.1054
AADTTCoringLane	0.0006	0.0004	1.6186	0.1212

Residual standard error: 1.553 on 20 degrees of freedom; Multiple R-Squared: 0.69.

For RAC-O pavements

$$500Hz\ Sound\ Intensity(dBA) = 81.5994 + 0.1697 \times AirVoid(\%) + 0.1673 \times Age(year) - 0.0411 \times FinenessModulus + 0.0039 \times MPD(micron) + 0.0186 \times Thickness(mm) - 0.0117 \times NumberOfDays > 30C + 0.0005 \times AADTTinCoringLane \quad \textbf{(A.5.11)}$$

Table A.22: Regression Analysis of Multiple-Variable Models for Sound Intensity at 500 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	81.5994	13.8678	5.8841	0
AirVoid	0.1697	0.211	0.8043	0.427
Age	0.1673	0.1595	1.0489	0.3019
FinenessModulus	-0.0411	3.0992	-0.0133	0.9895
MPD	0.0039	0.002	1.9876	0.05
Thickness	0.0186	0.0463	0.4015	0.6907
NoDaysTempGT30	-0.0117	0.0087	-1.3398	0.1895
AADTTCoringLane	0.0005	0.0002	2.4454	0.02

Residual standard error: 2.156 on 33 degrees of freedom; Multiple R-Squared: 0.55.

All four models show large variance in the 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. Truck traffic volume is a significant factor that contributes to the increase of the 500-Hz band noise for open-graded mixes, but not for dense- or gap-graded mixes. The estimated coefficients (0.001 for OGAC versus 0.0005 for RAC-O) indicate that the traffic effect is more pronounced on the OGAC pavements than on the RAC-O pavements.

Among the four mix types, air-void content is statistically significant at the 95 percent confidence level only for OGAC pavements. The estimated coefficient indicates that higher air-void content increases the 500-Hz band noise due to an increase in tire vibration.

For all pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect the low-frequency noise. The number of high temperature days is a statistically significant variable for OGAC. More high temperature days tend to result in lower low-frequency noise on OGAC pavements.

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.

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.11 shows the 1,000-Hz OBSI values observed in the five survey years on each pavement section for the four mix types. Generally the 1,000-Hz sound intensity increases with pavement age, except for RAC-O where there does not appear to be much 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) 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 most likely it is primarily affected by tire tread pattern and not pavement characteristics.

Figure A.22 shows the box plots of 1,000-Hz OBSI for five years of measurement for different mix types for the three initial age categories. Other than a few exceptions in the RAC-O mixes, sound intensity increases 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 is the lowest on RAC-O pavements, which means that RAC-O pavements retain their noise-reducing properties over a longer period.

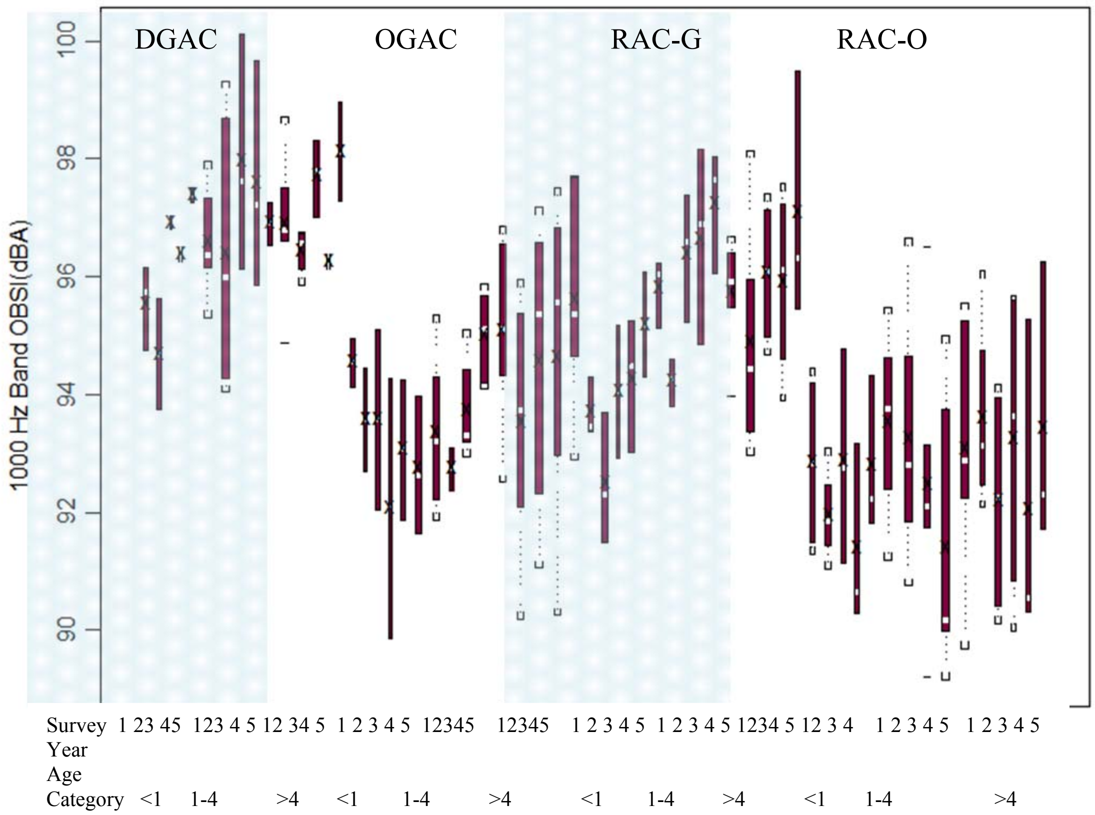


Figure A.22: Sound intensity at 1,000 Hz for different initial age categories (Age Category) and for five years of data collection.

Figure A.23 shows the estimated cumulative distribution function of 1,000-Hz noise reduction for both the OGAC and RAC-O types of open-graded mixes and the RAC-G mixes compared to the average 1,000-Hz noise levels of DGAC mixes in six age groups. The average 1,000-Hz noise level on DGAC pavements, as shown in the legend, is approximately 95.6 dB(A) for newly paved overlays, between approximately 96 and 97 dB(A) for pavements with an age between three and nine years, and approximately 97.3 dB(A) for pavements older than nine years. A negative value in Figure A.23 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, OGAC, RAC-G, and RAC-O pavements are all generally quieter than the DGAC pavements in terms of 1,000-Hz band noise.

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

For pavements with an age between one and three years, OGAC and RAC-O pavements have similar noise-reducing properties (about 70 percent of the pavements are at least 3 dB[A] quieter than average DGAC pavement), while RAC-G pavements begin to lose their noise-reducing effect.

For pavements with an age between three and five years, OGAC and RAC-O pavements still have similar noise-reducing properties, which are better than RAC-G pavements. About 80 percent of RAC-O and OGAC pavements, and 10 percent of RAC-G pavements are at least 3 dB(A) quieter than the average DGAC pavement. Interestingly, some RAC-O pavements can provide a noise-reducing effect up to 6 dB(A) compared to DGAC pavements of similar age.

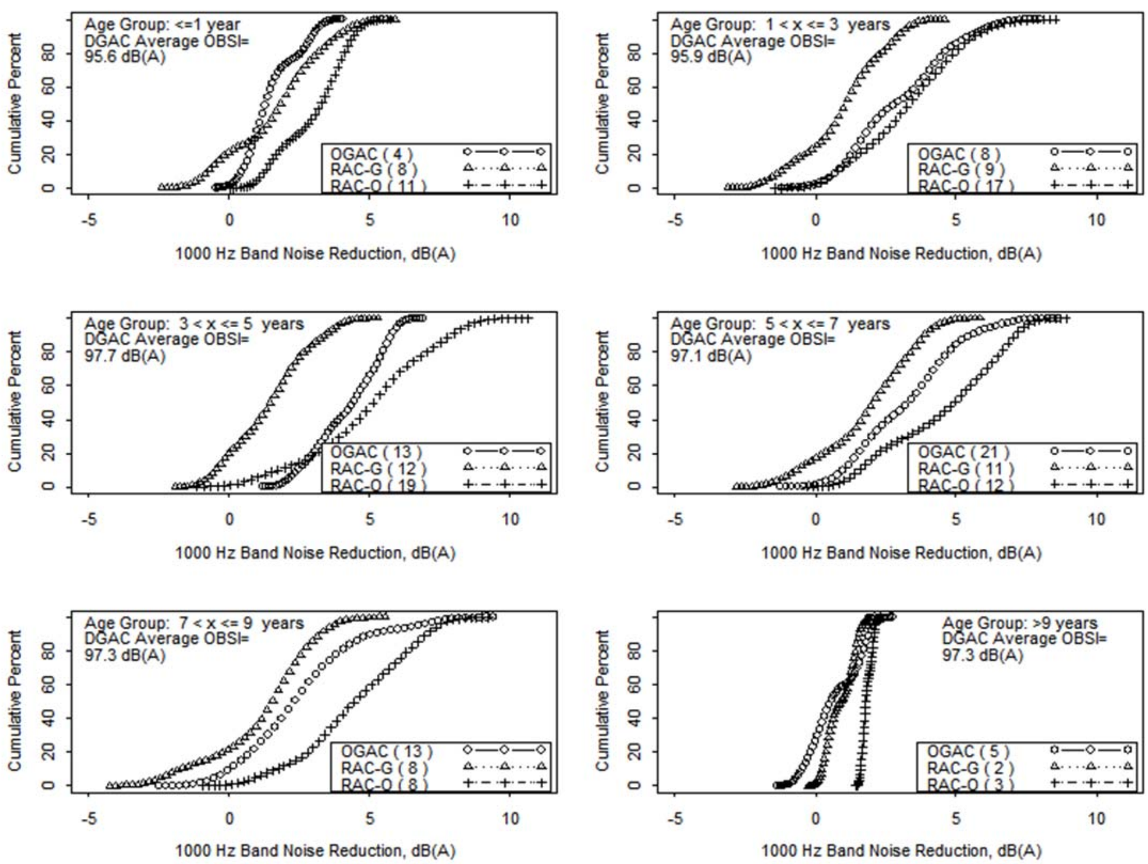


Figure A.23: Estimated cumulative distribution function of 1,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.).

For pavements with an age between five and nine years, RAC-O, OGAC, and RAC-G pavements show different noise-reducing properties, with RAC-O still doing the better job at reducing noise than others. About 20 percent of RAC-O pavements in this category can provide up to a 6 dB(A) noise-reducing benefit. None of the pavements with ages greater than nine years is able to provide a 3 dB(A) noise-reducing benefit compared with DGAC. The rank of the three mixes from best to worst is RAC-O, RAC-G, and 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. Compared to the analysis performed for the four-year report, MPD was used as a surrogate for the surface distresses used in the model (raveling and rutting). In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as independent variables, while mix property variables are excluded. The regression equation appears as Equation A.5.12:

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

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.23: 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)	96.9784	0.6131	158.179	0
Age	0.2085	0.0353	5.9066	0
PvmntTypeOGAC	-3.3753	0.3756	-8.9857	0
PvmntTypeRAC-G	-1.5512	0.328	-4.7294	0
PvmntTypeRAC-O	-4.7398	0.3669	-12.9176	0
Thickness	-0.0289	0.0067	-4.3142	0
NoDaysTempGT30	0.0102	0.002	5.1123	0
AADTTCoringLane	0	0.0001	0.4899	0.6247
MPD	-0.0005	0.0004	-1.329	0.1852

Residual standard error: 1.535 on 226 degrees of freedom; Multiple R-Squared: 0.58.

At the 95 percent confidence level, age, mix type, surface layer thickness, and number of high temperature days significantly affect the 1,000-Hz sound intensity. 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, 1.6, and 4.7 dB(A), respectively. The interaction terms between age and mix type were studied and 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 among the four pavement types.

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

For DGAC pavements

$$1000Hz\ Sound\ Intensity(dBA) = 95.2679 + 0.3472 \times AirVoid(\%) - 0.0727 \times Age(year) - 1.0825 \times FinenessModulus + 0.0039 \times MPD + 0.0054 \times Thickness(mm) + 0.0045 \times NumberOfDays > 30C + 0.0004 \times AADTTinCoringLane \quad \textbf{(A.5.13)}$$

Table A.24: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	95.2679	3.9891	23.882	0
AirVoid	0.3472	0.1785	1.9446	0.0668
Age	-0.0727	0.0853	-0.8519	0.4049
FinenessModulus	-1.0825	0.9834	-1.1007	0.2848
MPD	0.0039	0.0018	2.2319	0.0379
Thickness	0.0054	0.0148	0.3664	0.7181
NoDaysTempGT30	0.0045	0.0055	0.8141	0.4257
AADTTCoringLane	0.0004	0.0002	2.4018	0.0267

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

For OGAC pavements

$$1000Hz\ Sound\ Intensity(dBA) = 100.5574 - 0.1519 \times AirVoid(\%) + 0.1263 \times Age(year) - 1.5119 \times FinenessModulus + 0.0023 \times MPD(micron) - 0.0391 \times Thickness(mm) + 0.008 \times NumberOfDays > 30C + 0.0007 \times AADTTinCoringLane \quad \textbf{(A.5.14)}$$

Table A.25: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	100.5574	5.4188	18.5571	0
AirVoid	-0.1519	0.1282	-1.185	0.2457
Age	0.1263	0.0939	1.3449	0.1891
FinenessModulus	-1.5119	1.2307	-1.2284	0.2292
MPD	0.0023	0.0013	1.7554	0.0898
Thickness	-0.0391	0.0223	-1.7505	0.0906
NoDaysTempGT30	0.008	0.0053	1.5238	0.1384
AADTTCoringLane	0.0007	0.0003	2.6448	0.0131

Residual standard error: 1.3 on 29 degrees of freedom; Multiple R-Squared: 0.58.

For RAC-G pavements

$$1000Hz\ Sound\ Intensity(dBA)\text{=}85.4012\text{-}0.1902\times AirVoid(\%)+0.2179\times Age(year)+1.8515\times FinenessModulus+0.0015\times MPD(micron)$$
$$-0.025\times Thickness(mm)+0.0125\times NumberOfDays>30C+0.0001\times AADTTinCoringLane \quad \textbf{(A.5.15)}$$

Table A.26: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	85.4012	7.0153	12.1735	0
AirVoid	-0.1902	0.1561	-1.2182	0.2373
Age	0.2179	0.1157	1.8834	0.0743
FinenessModulus	1.8515	1.4906	1.2422	0.2285
MPD	0.0015	0.0014	1.0869	0.29
Thickness	-0.025	0.0223	-1.1224	0.275
NoDaysTempGT30	0.0125	0.0051	2.4455	0.0238
AADTTCoringLane	0.0001	0.0003	0.3275	0.7467

Residual standard error: 1.33 on 20 degrees of freedom; Multiple R-Squared: 0.50.

For RAC-O pavements

$$1000Hz\ Sound\ Intensity(dBA)\text{=}107.4067\text{+}0.1122\times AirVoid(\%)+0.1726\times Age(year)-1.9893\times FinenessModulus-0.0028\times MPD(micron)$$
$$-0.1097\times Thickness(mm)-0.0003\times NumberOfDays>30C-0.0002\times AADTTinCoringLane \quad \textbf{(A.5.16)}$$

Table A.27: Regression Analysis of Multiple-Variable Models for Sound Intensity at 1,000 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	107.4067	9.0543	11.8625	0
AirVoid	0.1122	0.1377	0.8144	0.4212
Age	0.1726	0.1041	1.6572	0.1069
FinenessModulus	-1.9893	2.0235	-0.9831	0.3327
MPD	-0.0028	0.0013	-2.1837	0.0362
Thickness	-0.1097	0.0302	-3.6319	0.0009
NoDaysTempGT30	-0.0003	0.0057	-0.0601	0.9524
AADTTCoringLane	-0.0002	0.0001	-1.3344	0.1912

Residual standard error: 1.408 on 33 degrees of freedom; Multiple R-Squared: 0.53.

All regression equations have low R^2 values (around 0.55), indicating that there is an explanatory variable other than the traffic, climate, and pavement variables to be considered here. The tire tread pattern for the SRTT is likely to primarily control the noise level for this frequency, as was discussed in the fourth-year report. The results show that at a 95 percent confidence level, although age is not significant for all pavement surface types, the estimated parameters indicate that the 1,000-Hz sound intensity increases with pavement age for all four mix types. Air-void content is insignificant 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 for only RAC-O and DGAC pavements, and a higher MPD value corresponds to a higher noise level on DGAC, OGAC, and RAC-G pavements, but to a lower noise level on RAC-O pavements.

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 traffic results in higher noise level at 1,000 Hz.

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.14 shows the 2,000-Hz OBSI values observed in the five survey years on each pavement section for 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 have significantly lower sound intensities at 2,000-Hz than dense-graded surfaces (DGAC).

Figure A.24 shows the box plots of 2,000-Hz OBSI in five years for different mix types for three age categories. As the figure shows, sound intensity generally increases with pavement age for the same pavement sections. The rate of increase in sound intensity with age at 2,000 Hz is the lowest for RAC-O pavements.

Figure A.25 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, is approximately 88.8 dB(A) for newly paved overlays, between 90.0 and 90.9 dB(A) for pavements with ages between three and nine years, and approximately 91.3 dB(A) for pavements older than nine years.

A positive value in Figure A.25 indicates reduction in noise levels compared to the average DGAC mix noise level. It is evident that OGAC, RAC-G, and RAC-O pavements are all quieter than the DGAC pavements in terms of 2,000-Hz band noise. With the exception of a few outliers, the noise reduction is generally between -2 and 11 dB(A) for open-graded pavements, between -2 and 6 dB(A) for RAC-G pavements, and between 0 and 11 dB(A) for RAC-O pavements.

For newly paved overlays (age less than or equal to one year), OGAC pavements have better noise-reducing properties than other pavements, and can provide up to a 6 dB(A) noise-reducing benefit. If at least a 3 dB(A) noise reduction is required for a surface to be considered noise-reducing, all OGAC pavements, 80 percent of RAC-O pavements, and 40 percent of RAC-G pavements are noise-reducing for new pavement.

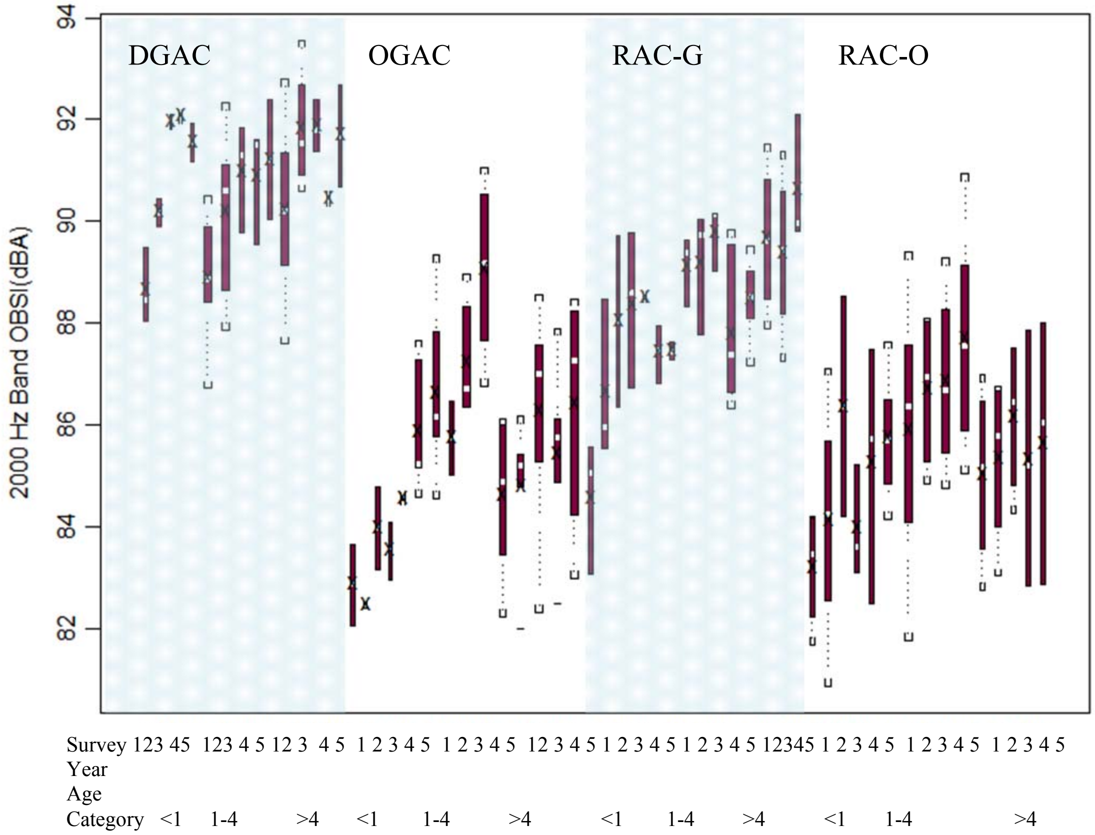


Figure A.24: Sound intensity at 2,000 Hz for different initial age categories (Age Category) and for five years of data collection.

For pavements with ages between one and three years, OGAC and RAC-O pavements have similar noise-reducing ability (about 70 percent are at least 3 dB[A] quieter than average DGAC pavement), while only 15 percent of RAC-G pavements are at least 3 dB(A) quieter than the average DGAC pavement. As explained in previous reports, the RAC-G mixes in the sample were generally poorly compacted and behaved almost as if they were open-graded. They were compacted by traffic in the wheelpath and have lower air-void contents and less ability to reduce the air-pumping noise mechanism.

For pavements with ages between three and nine years, RAC-O and OGAC pavements seem to have similar performance, and about 80 percent of these section have a noise level at least 3 dB(A) less than DGAC.

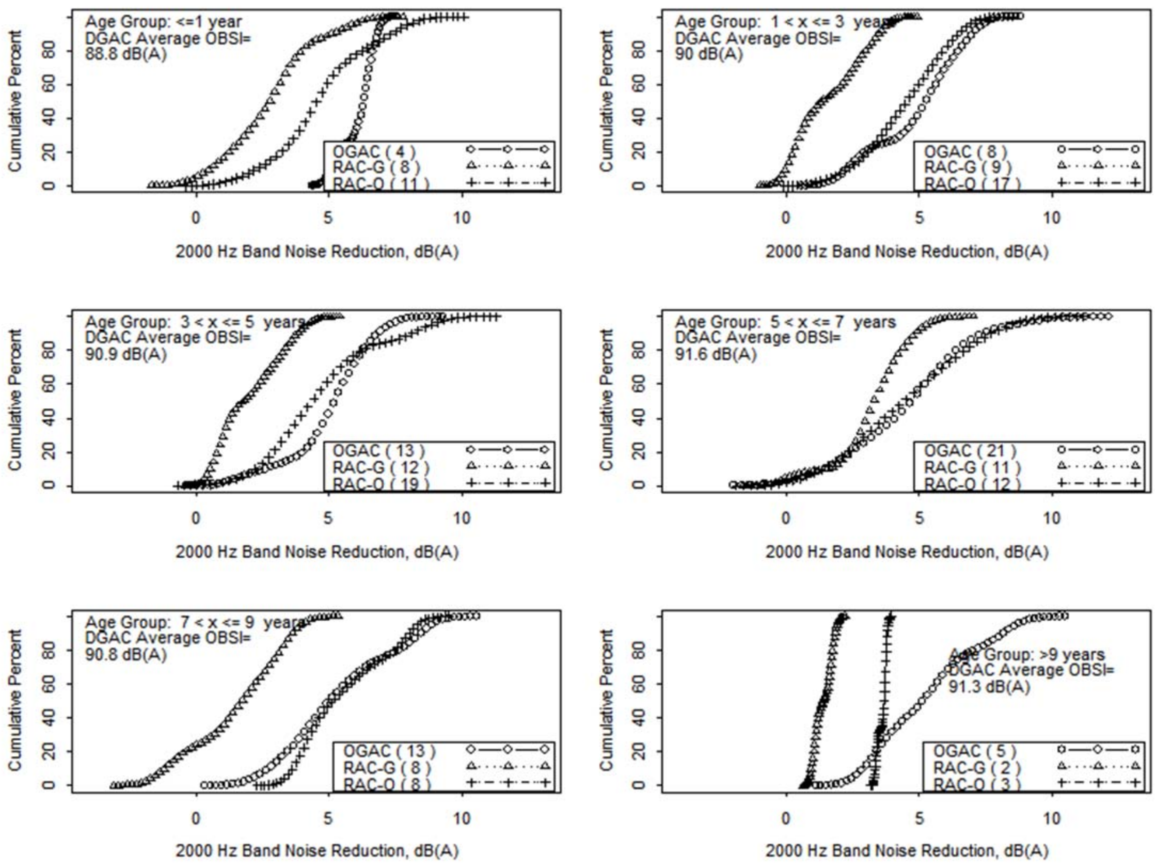


Figure A.25: Estimated cumulative distribution function of 2,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type;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

For pavements older than nine years all pavement types have better performance than DGAC, with OGAC being the best. About 60 percent of the OGAC pavements can provide up to a 6 dB(A) noise benefit. Almost all of the RAC-O pavements always provide at least 3 dB(A) 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. Compared to the analysis performed for four-year report, MPD was used as a surrogate for the surface distresses used in the model (raveling and rutting). In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as independent variables, while mix property variables are excluded. The regression equation appears as Equation A.5.17:

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

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.28: 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)	89.5366	0.6713	133.3701	0
Age	0.3077	0.0387	7.9586	0
PvmntTypeOGAC	-4.266	0.4113	-10.3717	0
PvmntTypeRAC-G	-1.8879	0.3592	-5.2565	0
PvmntTypeRAC-O	-4.0421	0.4018	-10.0604	0
Thickness	0.0021	0.0073	0.2817	0.7784
NoDaysTempGT30	0.0074	0.0022	3.3666	0.0009
AADTTCoringLane	0	0.0001	-0.3671	0.7139
MPD	-0.0015	0.0004	-3.6091	0.0004

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. All three pavement types, OGAC, RAC-G, and RAC-O, 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, 1.9, and 4.0 dB(A), respectively. MPD is a significant factor and higher MPD values decrease the sound level at 2,000 Hz. Moreover, MPD is indirectly related to the air-void content and higher air content will reduce the air pumping effect and lower the sound level at 2,000 Hz. It is therefore likely that the higher air-void content is responsible for the reduced noise, and not MPD itself. The interaction terms between age and mix type are statistically insignificant, 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 is replaced with mix property variables and the model is estimated for each mix type separately. The regression equations appear as Equation A.5.18 through Equation A.5.21:

For DGAC pavements

$$2000Hz\ Sound\ \ Intensity(dBA) = 93.8228 - 0.3696\times AirVoid(\%) + 0.1518\times Age(year) - 0.676\times FinenessModulus + 0.0021\times MPD - 0.0306\times Thickness(mm) + 0.0032\times NumberOfDays > 30C + 0.0004\times AADTTinCoringLane \quad \textbf{(A.5.18)}$$

Table A.29: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	93.8228	4.1465	22.6267	0
AirVoid	-0.3696	0.1856	-1.9917	0.061
Age	0.1518	0.0887	1.712	0.1032
FinenessModulus	-0.676	1.0222	-0.6613	0.5164
MPD	0.0021	0.0018	1.1543	0.2627
Thickness	-0.0306	0.0154	-1.9816	0.0622
NoDaysTempGT30	0.0032	0.0057	0.5638	0.5795
AADTTCoringLane	0.0004	0.0002	2.1729	0.0426

Residual standard error: 1.156 on 19 degrees of freedom; Multiple R-Squared: 0.64.

For OGAC pavements

$$2000Hz\ Sound\ Intensity(dBA) = 90.0564 - 0.2363 \times AirVoid(\%) + 0.2451 \times Age(year) - 0.1587 \times FinenessModulus - 0.001 \times MPD(micron) + 0.0158 \times Thickness(mm) - 0.0055 \times NumberOfDays > 30C - 0.0007 \times AADTTinCoringLane \quad \textbf{(A.5.19)}$$

Table A.30: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	90.0564	4.5961	19.5943	0
AirVoid	-0.2363	0.1087	-2.1732	0.0381
Age	0.2451	0.0797	3.0767	0.0045
FinenessModulus	-0.1587	1.0439	-0.1521	0.8802
MPD	-0.001	0.0011	-0.862	0.3958
Thickness	0.0158	0.0189	0.8336	0.4113
NoDaysTempGT30	-0.0055	0.0045	-1.2276	0.2295
AADTTCoringLane	-0.0007	0.0002	-3.0089	0.0054

Residual standard error: 1.103 on 29 degrees of freedom; Multiple R-Squared: 0.74.

For RAC-G pavements

$$2000Hz\ Sound\ Intensity(dBA) = 80.4338 - 0.4294 \times AirVoid(\%) + 0.2504 \times Age(year) + 2.0439 \times FinenessModulus + 0.0011 \times MPD(micron) - 0.0439 \times Thickness(mm) + 0.0043 \times NumberOfDays > 30C + 0.0007 \times AADTTinCoringLane \quad \textbf{(A.5.20)}$$

Table A.31: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	80.4338	5.3236	15.1088	0
AirVoid	-0.4294	0.1184	-3.6248	0.0017
Age	0.2504	0.0878	2.8522	0.0098
FinenessModulus	2.0439	1.1311	1.8069	0.0858
MPD	0.0011	0.001	1.0797	0.2931
Thickness	-0.0439	0.0169	-2.5948	0.0173
NoDaysTempGT30	0.0043	0.0039	1.1177	0.2769
AADTTCoringLane	0.0007	0.0002	2.7807	0.0115

Residual standard error: 1.009 on 20 degrees of freedom; Multiple R-Squared: 0.71.

For RAC-O pavements

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

Table A.32: Regression Analysis of Multiple-Variable Models for Sound Intensity at 2,000 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	112.124	7.315	15.3279	0
AirVoid	-0.1058	0.1113	-0.9504	0.3488
Age	0.3831	0.0841	4.5545	0.0001
FinenessModulus	-5.0247	1.6348	-3.0736	0.0042
MPD	-0.0007	0.001	-0.7103	0.4825
Thickness	-0.0077	0.0244	-0.3152	0.7546
NoDaysTempGT30	-0.0006	0.0046	-0.1309	0.8966
AADTTCoringLane	0.0003	0.0001	2.574	0.0147

Residual standard error: 1.137 on 33 degrees of freedom; Multiple R-Squared: 0.71.

Generally the R^2 are fairly good and around 0.7 for the open-graded mixes. The results of multiple linear regression analysis show that the 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 and DGAC mixes. At the 95 percent confidence level, pavement age is a significant factor for all mix types except DGAC. Older pavements have higher 2,000 Hz sound intensities. The surface layer thickness is significant for RAC-G pavements. Generally, a thicker surface layer corresponds to a lower 2,000-Hz sound intensity. Truck traffic volume is a significant factor that increases tire/pavement noise for all four mix types. Surface macrotexture (MPD) is not a significant variable for any of the mixes. Fineness modulus is only significant for RAC-O pavements. Generally a higher fineness modulus results in a lower sound intensity at 2,000 Hz.

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.17 shows the 4,000-Hz OBSI values observed on each pavement section for the four mix types for the five survey years. Overall, it appears that the 4,000-Hz sound intensity increases significantly with age for only RAC-G pavements. For OGAC pavements, the 4,000-Hz sound intensity increases with age for newly paved overlays but tends to stabilize or even decrease slightly with age for pavements older than four years. On RAC-G pavements, the 4,000-Hz sound intensity increases with pavement age for both newly paved and older pavements. For DGAC pavements, the 4,000-Hz sound intensity increases slightly with age for newly paved overlays and remains constant for older sections, as well. For RAC-O pavements, the 4,000-Hz sound intensity trend is unclear.

Figure A.26 shows the box plots of 4,000-Hz OBSI in five years for different mix types for three age categories. As the figure shows, 4,000-Hz band sound intensity generally increases with age for the same pavement section. Newly overlaid OGAC, RAC-O, and RAC-G sections have significantly lower 4,000 Hz sound intensity values than DGAC sections. DGAC sections exhibit 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 may exhibit lower 4,000-Hz band sound intensity than younger pavements. This trend is more pronounced in sections that are more than four years old.

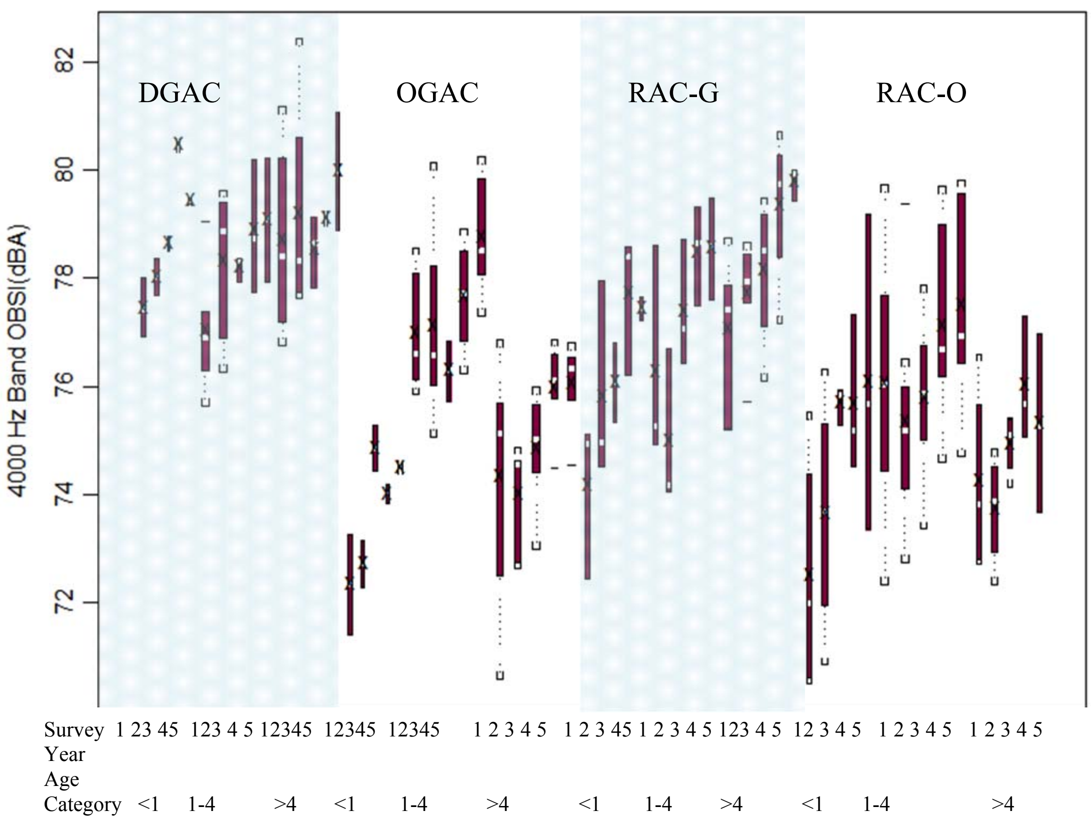


Figure A.26: Sound intensity at 4,000 Hz for different initial age categories (Age Category) and for five years of data collection.

Figure A.27 shows 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 legend, is about 77.2 dB(A) for newly paved overlays, between approximately 78.1 and 79.6 dB(A) for pavements with ages between three and nine years, and around 78.4 dB(A) for pavements older than nine years. The narrow range of sound intensities for DGAC pavements indicates that the 4,000-Hz noise level on DGAC pavements does not change significantly with age.

A positive value in Figure A.27 indicates a reduction in noise levels compared to the average DGAC mix noise level. The figure shows that for the most part the open-graded (OGAC and RAC-O) pavements are quieter than the DGAC pavements in terms of 4,000-Hz band noise. RAC-G pavements with an age between zero and seven years also exhibited lower 4,000-Hz band noise, but RAC-G pavements with an age 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 is generally between -3 and 10 dB(A) for open-graded pavements, between -5 and 10 dB(A) for RAC-O pavements, and between -5 and 4 dB(A) for RAC-G pavements.

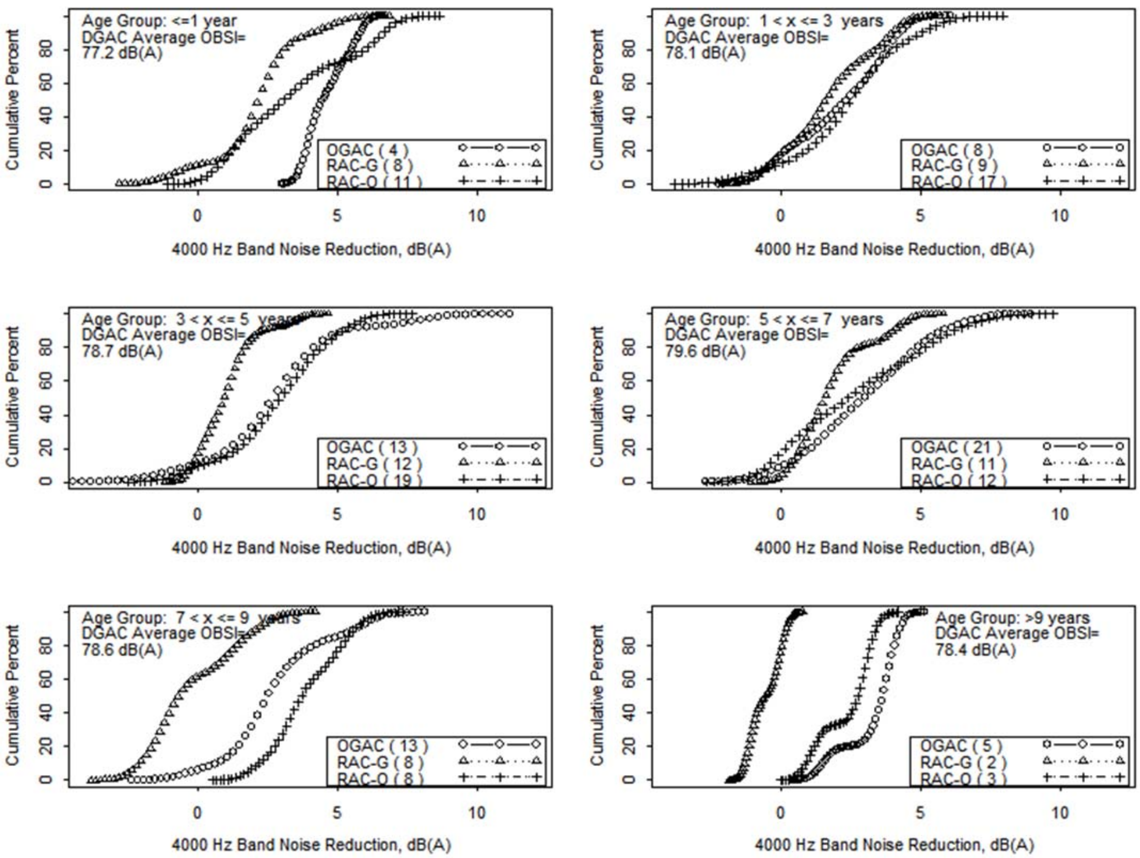


Figure A.27: Estimated cumulative distribution function of 4,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups by pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

For newly paved overlays, the three mix types, OGAC, RAC-G, and RAC-O, exhibit similar noise-reducing properties with OGAC being the best, providing a 3 dB(A) noise reduction all the time. For pavements with ages between one and three years and five to seven years, OGAC, RAC-G, and RAC-O, exhibit similar noise-reducing properties. All mixes can provide a 3 dB(A) noise reduction about 50 percent of the time compared with DGAC.

For pavements with ages between three to five years, RAC-G pavements lose their noise-reducing capability but OGAC and RAC-O can still provide up to a 3 dB(A) noise reduction 50 percent of the time. For pavements between seven and nine years old, RAC-O pavements do a better job in reducing noise. Moreover, 70 percent of RAC-O pavements can provide up to a 3 dB(A) reduction in noise while about 30 percent of OGAC pavements can provide the same noise reduction.

For pavements that are more than nine years old, OGAC pavement is the best option and more than 40 percent of the time can provide more than a 3 dB(A) noise reduction.

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. Compared to the analysis performed for four-year report, MPD was used as a surrogate for the surface distresses used in the model (raveling and rutting). In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as independent variables, while mix property variables are excluded. The regression equation appears as Equation A.5.22:

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

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.33: 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)	77.8702	0.6655	117.0136	0
Age	0.1773	0.0633	2.7996	0.0056
PvmntTypeOGAC	-1.8728	0.631	-2.9681	0.0033
PvmntTypeRAC-G	-2.1078	0.572	-3.6847	0.0003
PvmntTypeRAC-O	-2.608	0.5754	-4.5327	0
Thickness	0.0166	0.0068	2.4528	0.0149
NoDaysTempGT30	0.0044	0.002	2.1575	0.032
AADTTCoringLane	0.0004	0.0001	5.1966	0
MPD	-0.0025	0.0004	-6.4557	0
AgePvmntTypeOGAC	0.1167	0.0932	1.2526	0.2117
AgePvmntTypeRAC-G	0.3319	0.0929	3.5735	0.0004
AgePvmntTypeRAC-O	0.133	0.0906	1.4687	0.1433

Residual standard error: 1.54 on 223 degrees of freedom; Multiple R-Squared: 0.59.

At a 95 percent confidence level, age, pavement type, thickness, number of days with temperature higher than 30°C, 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 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 1.8, 2.1, and 2.6 dB(A), respectively. The 4,000-Hz sound intensity also increases with truck traffic volume and surface layer thickness. Sound intensity at 4,000 Hz decreases as MPD increases. Moreover, MPD is an indirect representation of air void and usually mixes with higher MPD have higher air void. A higher air-void content can reduce the air pumping effect of a rolling tire, which mostly affects the noise level at high frequencies. Among all mix types, the rate of increase in 4,000 Hz sound intensity for RAC-G is significantly higher than all other mixes.

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

<u>For DGAC pavements</u>

$$\begin{aligned} &4000Hz\ Sound\ Intensity(dBA) = 82.3286 - 0.5077 \times AirVoid(\%) + 0.1242 \times Age(year) - 0.2769 \times FinenessModulus \\ &+ 0.0006 \times MPD - 0.0348 \times Thickness(mm) + 0.0049 \times NumberOfDays > 30C + 0.0004 \times AADTTinCoringLane \end{aligned} \quad \textbf{(A.5.23)}$$

Table A.34: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for DGAC

	Value	Std. Error	t value	P-value
(Intercept)	82.3286	3.449	23.8702	0
AirVoid	-0.5077	0.1544	-3.2894	0.0039
Age	0.1242	0.0737	1.6846	0.1084
FinenessModulus	-0.2769	0.8503	-0.3256	0.7483
MPD	0.0006	0.0015	0.3975	0.6954
Thickness	-0.0348	0.0128	-2.7119	0.0138
NoDaysTempGT30	0.0049	0.0047	1.0295	0.3162
AADTTCoringLane	0.0004	0.0001	2.9221	0.0087

Residual standard error: 0.9614 on 19 degrees of freedom; Multiple R-Squared: 0.73.

For OGAC pavements

$$4000Hz\ Sound\ Intensity(dBA) = 87.6269 - 0.1313 \times AirVoid(\%) + 0.2394 \times Age(year) - 1.4845 \times FinenessModulus - 0.004 \times MPD(micron) + 0.05 \times Thickness(mm) - 0.01 \times NumberOfDays > 30C + 0.0003 \times AADTTinCoringLane \quad \textbf{(A.5.24)}$$

Table A.35: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for OGAC

	Value	Std. Error	t value	P-value
(Intercept)	87.6269	4.5512	19.2538	0
AirVoid	-0.1313	0.1077	-1.22	0.2323
Age	0.2394	0.0789	3.0342	0.005
FinenessModulus	-1.4845	1.0337	-1.4361	0.1617
MPD	-0.004	0.0011	-3.691	0.0009
Thickness	0.05	0.0188	2.6653	0.0124
NoDaysTempGT30	-0.01	0.0044	-2.2648	0.0312
AADTTCoringLane	0.0003	0.0002	1.5965	0.1212

Residual standard error: 1.092 on 29 degrees of freedom; Multiple R-Squared: 0.80.

For RAC-G pavements

$$4000Hz\ Sound\ Intensity(dBA) = 72.739 - 0.2877 \times AirVoid(\%) + 0.3161 \times Age(year) + 1.0164 \times FinenessModulus + 0.0013 \times MPD(micron) - 0.0199 \times Thickness(mm) - 0.0109 \times NumberOfDays > 30C + 0.0008 \times AADTTinCoringLane \quad \textbf{(A.5.25)}$$

Table A.36: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for RAC-G

	Value	Std. Error	t value	P-value
(Intercept)	72.739	6.883	10.5679	0
AirVoid	-0.2877	0.1531	-1.8787	0.0749
Age	0.3161	0.1135	2.7847	0.0114
FinenessModulus	1.0164	1.4624	0.695	0.495
MPD	0.0013	0.0013	1.0097	0.3247
Thickness	-0.0199	0.0219	-0.9097	0.3738
NoDaysTempGT30	-0.0109	0.005	-2.181	0.0413
AADTTCoringLane	0.0008	0.0003	2.6249	0.0162

Residual standard error: 1.305 on 20 degrees of freedom; Multiple R-Squared: 0.63.

For RAC-O pavements

$$4000 Hz\ Sound\ Intensity(dBA) = 104.5939 - 0.1309 \times AirVoid(\%) + 0.4104 \times Age(year) - 5.6904 \times FinenessModulus - 0.0018 \times MPD(micron) + 0.0152 \times Thickness(mm) + 0.0032 \times NumberOfDays > 30C + 0.0009 \times AADTTinCoringLane \quad \textbf{(A.5.26)}$$

Table A.37: Regression Analysis of Multiple-Variable Models for Sound Intensity at 4,000 Hz for RAC-O

	Value	Std. Error	t value	P-value
(Intercept)	104.5939	6.9569	15.0346	0
AirVoid	-0.1309	0.1058	-1.2372	0.2247
Age	0.4104	0.08	5.1301	0
FinenessModulus	-5.6904	1.5548	-3.66	0.0009
MPD	-0.0018	0.001	-1.8561	0.0724
Thickness	0.0152	0.0232	0.654	0.5176
NoDaysTempGT30	0.0032	0.0044	0.7284	0.4715
AADTTCoringLane	0.0009	0.0001	7.7234	0

Residual standard error: 1.082 on 33 degrees of freedom; Multiple R-Squared: 0.82.

The results show that at a 95 percent confidence level, truck traffic volume is a significant factor for all the pavement types except OGAC: Higher traffic volume leads to a higher 4,000-Hz noise level. Air-void content is significant only for DGAC. Generally, a higher air-void content increases the 4,000 Hz sound intensity. 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. The aggregate gradation variable (fineness modulus) does not seem 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 significant on both OGAC and RAC-O pavements, and the estimated coefficients indicate that higher MPD values lead to lower 4,000-Hz noise levels, although as noted for the 2,000-Hz frequency data, this may be due to some cross-correlation with air-void content. Conversely for DGAC and RAC-G, pavements with higher MPD have higher 4,000-Hz noise levels.

Number of days with temperature greater than 30°C is only significant for RAC-G and OGAC pavements, and an increase in numbers of days with temperature higher than 30°C results in a decrease in the sound intensity at 4,000 Hz.

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 were similar to those of sound intensities at their adjacent frequency bands. For this reason, only the trends and models for the 500, 1,000, 2,000, and 4,000 Hz frequencies have been discussed in this report. For more information on these see Appendix B.4.

A.4.4: Summary of Findings

The following findings were obtained regarding overall sound intensity:

1. Overall tire/pavement noise generally increases with pavement age. The average noise level on DGAC pavements was about 101.3 dB(A) for newly paved overlays, 102.0 dB(A) for pavements between one and three years old, and between 103.3 and 103.9 dB(A) for pavements older than three years. 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. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes were about 3.7, 1.6, and 3.0 dB(A), respectively. After the pavements were exposed to traffic, the overall sound intensity measured on RAC-G pavements rapidly increased, due to densification under traffic and consequent reduction in air-voids and permeability, and became similar to what has been measured for DGAC pavements of similar ages. The overall sound intensity measured on the OGAC pavements did not change much for about six years and then increased quickly with pavement age. With a few exceptions, the overall sound intensity measured on the RAC-O pavements did not change much for about seven years and then increased quickly with pavement age. To date, the RAC-O mixes do not show much increase in noise as they get older. The ranking (from best to worst) of the four mix types in terms of noise reduction is RAC-O, OGAC, RAC-G, and DGAC.
2. Multiple regression analysis on all mixes shows that overall sound intensity increases with increased MPD values, and decreases with the increased surface layer thickness. Multiple regression analysis showed that the rate of increase in overall sound intensity is statistically higher for OGAC pavements. It was also noted that sections with higher numbers of days with temperature higher than 30°C have higher overall sound intensity. Multiple regression analysis on individual mix types was performed and the R^2 values were found to be relatively high, with values above 0.69. The results show that the in-situ permeability (or air-void content) is only a significant factor for RAC-G mixes. Generally, higher permeability leads to a lower noise level. For all four mix types, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. 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. Relative truck traffic volume is a significant factor that increases tire/pavement noise for DGAC and OGAC mixes. Thickness was found to be a significant factor for RAC-O mixes. Moreover, an increase in thickness decreases the overall sound intensity.

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

1. At low frequency rumble (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. At a frequency level of 800 Hz, the sound intensities measured on OGAC, RAC-G, and RAC-O pavements began to become 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.
2. For newly paved OGAC and RAC-O mixes, the sound intensities at the frequencies higher than 1,000 Hz remained constant with age in the first five years, but the sound intensities at low frequencies (630 to 800 Hz) increased with age. For newly paved DGAC and RAC-G mixes, the low frequency noise decreased with age in the first five years, while the sound intensities at frequencies over 1,000 Hz increased significantly with age.
3. For pavements with an initial age between one and four years, sound intensity increased slightly on both open-graded pavements (OGAC and RAC-O) for frequencies above 1,000 Hz. For frequencies below 1,000 Hz, sound intensity increased for RAC-G significantly while for other mix types remained unchanged over five years.
4. For the oldest pavements (initial age greater than four years), the overall sound intensity with age for all mix types slightly increased. The increase of sound intensity with age mainly occurred at frequencies between 1,000 Hz and 2,500 Hz on 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.

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

1. For newly paved overlays (age less than or equal to one year), OGAC and RAC-O pavements exhibited a statistically higher 500-Hz noise level than DGAC pavements. RAC-G pavements had statistically the same level of 500-Hz sound intensity as DGAC pavements. Regarding the MPD values measured on these pavements, for newly placed mixes, open-graded pavements had rougher surfaces that contributed to more tire vibration than dense- and gap-graded pavements. This rougher surface produced more noise at frequencies lower than 1,000 Hz. For pavements with ages between four and seven years, there was no significant difference in 500-Hz sound intensity among the four mixes. For old pavements (older than seven years), OGAC pavements had higher 500-Hz sound intensity than the other three pavement types, which indicates that OGAC pavements experienced more surface distresses (likely raveling) that led to more tire vibration than the other pavement types. Both RAC-O and RAC-G pavements older than nine years old performed better than DGAC and could reduce noise up to 3 dB(A). OGAC pavements older than nine years

old produced significantly more noise than DGAC pavements. Overall, the increase rate of 500-Hz sound intensity with age was lower on rubberized pavements (RAC-G and RAC-O) than on nonrubberized pavements (DGAC and OGAC).

2. Multiple regression analysis on all mixes shows that age, number of high temperature days, truck traffic in the coring lane, and MPD significantly affects the 500-Hz band sound intensity. The 500-Hz band noise increases with pavement age, truck traffic volume, and MPD, but decreases with number of high temperature days.
3. Multiple regression analysis on individual mix type shows that truck traffic volume is a significant factor that contributes to the increase of 500-Hz band noise for open-graded mixes, but not for dense- or gap-graded mixes. The traffic effect was more significant on the OGAC pavements than on the RAC-O pavements. For all pavements, the aggregate gradation variable (fineness modulus) did not seem to significantly affect the low-frequency noise. Air-void content significantly affected the 500-Hz noise intensity for OGAC mixes. MPD seemed to be statistically significant for all mixes except OGAC.

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

1. For newly paved sections, the 1,000-Hz sound intensity measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) was lower than the values measured on dense-graded pavements (DGAC). After the pavements were exposed to traffic, OGAC and RAC-O pavements had similar noise-reducing properties for about five years. After five years RAC-O pavements has a better sound-reducing effect than OGAC pavements. RAC-G pavements did not seem to have sound reducing effect after they were exposed to traffic. For pavements older than nine years, none of the mix types can provide a 3 dB(A) noise reduction.
2. 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.
3. Multiple regression analysis on individual mix type shows that air-void content is not a significant factor for all pavements. For 1,000-Hz sound intensity, the surface layer thickness is significant for OGAC and RAC-O pavements at a 10 percent significant level and is not significant for DGAC and RAC-G pavements. The estimated parameters indicate that a thicker open-graded surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor for DGAC and RAC-O pavements. A higher MPD value corresponds to a higher noise level on DGAC, OGAC, and RAC-G pavements, but a lower noise level on RAC-O pavements. Truck traffic is a significant factor for DGAC and OGAC pavements but not for RAC-G and RAC-O pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect the tire/pavement noise for any of the mixes.

The following findings were obtained regarding the 2,000 and 4,000-Hz band sound intensities:

1. For newly paved sections, the 2,000-Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) were significantly lower than the values measured on dense-graded pavements (DGAC). The 2,000-Hz sound intensity increased at all pavement ages on RAC-G pavements, but primarily in the early years only for DGAC, OGAC, and RAC-O pavements. The rate of increase in sound intensity with age at 2,000 Hz was the lowest for RAC-O pavements. The 4,000-Hz sound intensity level for OGAC and RAC-O was significantly lower than those of DGAC and RAC-G for newly paved and sections older than four years. For sections between three and nine years old, RAC-O and OGAC pavements can provide up to an 11 dB(A) reduction in sound intensity. For sections older than nine years, RAC-O seems to be the only option able to provide a 3 dB(A) sound-intensity reduction.
2. For all pavement types, the 4,000-Hz sound intensity of newly aged sections increased with age. For old sections, however, the rate of increase in high frequency sound intensity was more pronounced for RAC-G sections.
3. Multiple regression analysis for all mixes pooled together shows that age, mix type, number of high temperature days, and MPD significantly affect the 2,000-Hz band sound intensity. The 2,000-Hz band noise increases with pavement age and number of high temperature days, but decreases with MPD.
4. Multiple regression analysis on all mixes shows that age, mix type, number of high temperature days, layer thickness, MPD, and truck traffic significantly affect the 4000-Hz band sound intensity. The 4,000-Hz band noise increases with pavement age, number of high temperature days, layer thickness, and truck traffic but decreases with MPD.
5. For 2,000-Hz sound intensities, multiple regression analysis on individual mix type shows that air-void content is a significant factor for OGAC and RAC-G pavements, and is not significant for RAC-O and DGAC pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on any pavement type except RAC-O. For RAC-O pavements, a larger fineness modulus (coarser gradation) results in significantly lower tire/pavement noise in the 2,000-Hz band. Truck traffic is a significant factor for all pavement types and the 2,000 Hz sound intensity increases with an increase in truck traffic.
6. For 4,000-Hz sound intensities, multiple regression analysis on individual mix type shows that air-void content is only significant for DGAC pavements. An increase in the air-void content of DGAC mixes decreases the 4,000 Hz high frequency noise. Higher truck traffic volume is significant for all mixes except RAC-G. Higher truck traffic leads to a higher 4,000-Hz noise level. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on any pavement type except RAC-O. A higher fineness modulus for RAC-O pavements leads a lower 4,000 Hz sound intensity. Pavement surface macrotexture (MPD) is significant on both OGAC and RAC-O pavements, and higher

MPD values lead to a lower 4,000-Hz noise level. However, MPD is somewhat correlated with air-void content, and it is likely that the effect shown for MPD is at least partly related to higher air-void contents. Number of high temperature days is only significant for OGAC and RAC-G pavements, and higher numbers of high temperature days results in a lower 4,000-Hz sound intensity.

A.5: Environmental Sections Analysis

All the environmental test sections (ES sections) were tested during the five-year survey. This appendix section 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 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 have the same aggregate gradations; the DGAC mix has a slightly finer dense gradation than the Type D-MB mix. The MB mixes generally have lower stiffnesses than the other mix types at 20°C, and the DGAC mix has the highest stiffness.

The roughness and noise of these sections over a five-year period have been analyzed and compared based on mix type and varying thicknesses. The results answer this question:

- How does the performance of dry- (RUMAC-GG) and terminal-process rubber (MB) compare to wet-process asphalt rubber (RAC-G) and dense-graded asphalt concrete (DGAC) under the same traffic and climate with respect to noise and roughness?

Figure A.28 shows the five-year MPD values for the Fresno 33 sections. The figure shows that the RAC-G mixes have highest MPD values. Type G-MB mixes have the lowest MPD values. All sections show an increase in macrotexture values with age for the first four years, but MPD values remain the same for most of the sections in the fifth year. This figure also shows that the variation of the MPD values for the Type G-MB and Type D-MB values is the lowest among the pavement types.

Figure A.29 shows the five-year IRI values for the Fresno 33 sections. The figure shows that the RAC-G and RUMAC-GG mixes have the highest IRI values compared to the other mix types. The 45-mm Type G-MB section showed the lowest IRI values of the five. IRI generally did not change from year four to year five except for the two RAC-G mixes, which showed a significant increase from the fourth to fifth year. Thickness of the surface layer does not seem to play a major role in IRI, since the increase in the value of IRI for both 45 and 90 mm layers is not statistically different.

Figure A.30 shows the five-year overall sound intensity levels for the Fresno 33 sections. The figure shows that the noise level increased slightly—less than 1 dB(A)—for all mixes from year four to year five, except for the RAC-G 45 mm, DGAC, and RUMAC-GG 45 mm. The RAC-G 45 mm mixes exhibit the highest noise level with 104.7 dB(A) and the Type G-MB 45 mm mixes exhibit the lowest noise intensity with the value of 102.7 dB(A). The fifth-year noise spectra, as shown in Appendix B.5, reveal that the noise increases occurred across low frequencies, particularly for the RAC-G 45 mm mixes, indicating that the increase of overall noise is caused by an increase in the surface texture that causes more tire vibration (at low frequencies). Figure A.30 also shows that there seems to be an interaction between increase in noise level and layer thickness since the sections with higher thickness experience a smaller increase in the overall sound level.

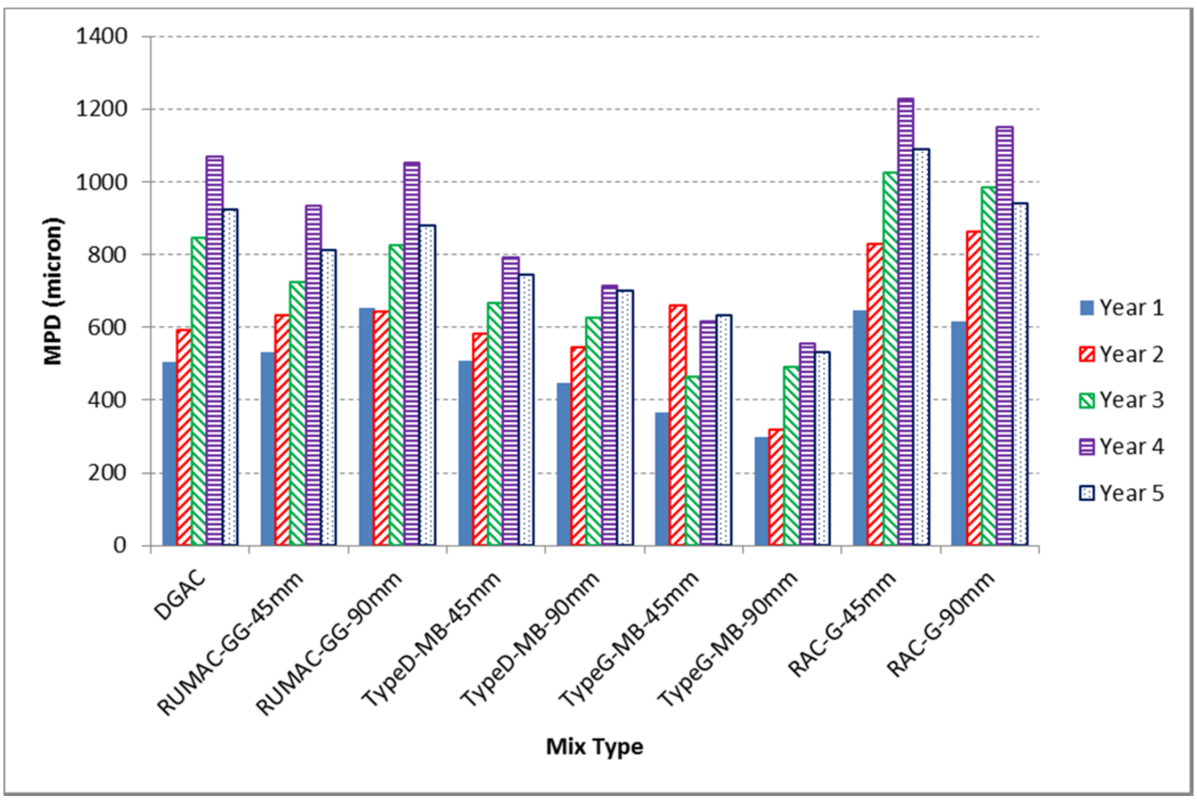


Figure A.28: Five-year MPD values for Fresno 33 sections.

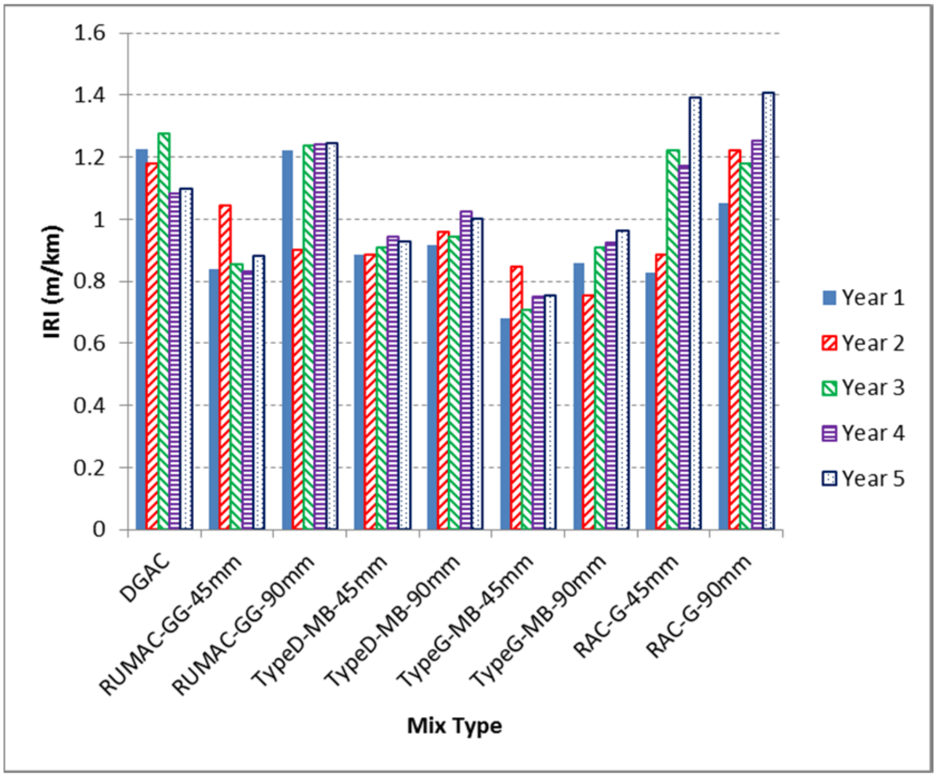


Figure A.29: Five-year IRI values for Fresno 33 sections.
(Note: 1 m/km = 63 in./mi)

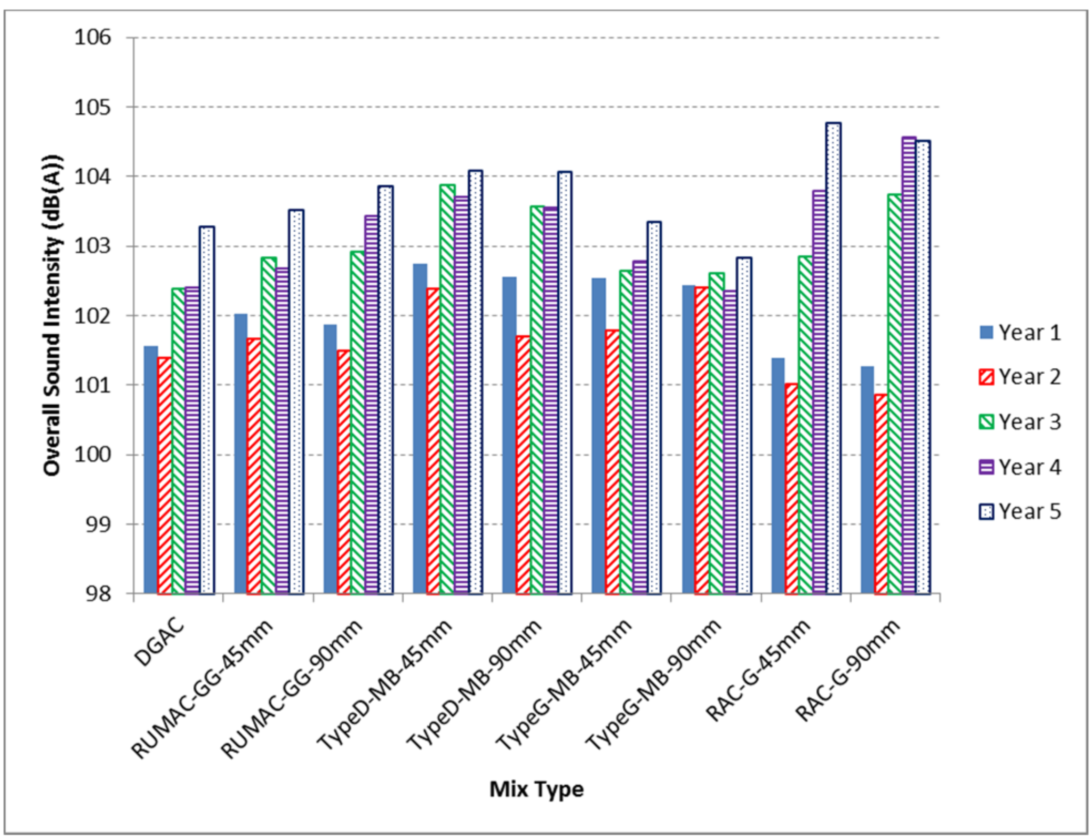


Figure A.30: Five-year overall OBSI values for Fresno 33 sections.

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 Sacramento 5 sections (same overlay in two directions of travel) have thicknesses around 30 mm, and the San Mateo 280 section has a thickness of 40 mm. The Sacramento 5 site was evaluated for both the northbound (NB) and southbound (SB) directions, while San Mateo 280 was evaluated only for the northbound direction. The Sacramento 5 sections were one year old and the San Mateo section was three years old during the first-year measurements. Both sites have an NMAS of 12.5 mm.

Roughness and noise of the different mixes over a five-year period were analyzed and compared for the northbound and southbound directions for the Sacramento 5 sections. The results answer the following questions:

- How does the performance of the Sacramento 5 and San Mateo 280 sections, which are overlays of PCC, compare to the performance of RAC-O mixes that are placed over asphalt pavement in terms of noise and roughness?
- Are there any differences between the performance in the northbound and southbound directions of the Sacramento 5 sections?

According to the study performed in the first year of data collection, the permeability/air-void content in the northbound direction of the Sacramento 5 sections is greater than that in the southbound direction. The San Mateo 280 section has lower air-void content but much higher permeability values than the Sacramento 5 sections *(1).*

Figure A.31 shows the five-year IRI values for the Sacramento 5 and San Mateo 280 sites. Both sites have "acceptable" ride quality based on overall FHWA criteria (IRI values less than 2.68 m/km [170 in./mi]). Sacramento 5 SB and San Mateo 280 are considered by FHWA to be "fair" for interstate highways (less than 1.88 m/km [119 in./mi]) and Sacramento 5 NB is considered to be mediocre for an interstate highway (less than 2.68 m/km [169.8 in./mi]) *(2).* The results of the first two years of data analysis showed that both the Sacramento 5 and San Mateo 280 sites have higher IRI values than the majority of the Quieter Pavement (QP) sections, probably due to the cracked PCC underneath, which produces a high IRI value *(1).* Figure A.31 shows that IRI generally remained constant from year four to year five except for Sacramento 5 NB, which experienced a 22 percent increase in IRI from year four to year five.

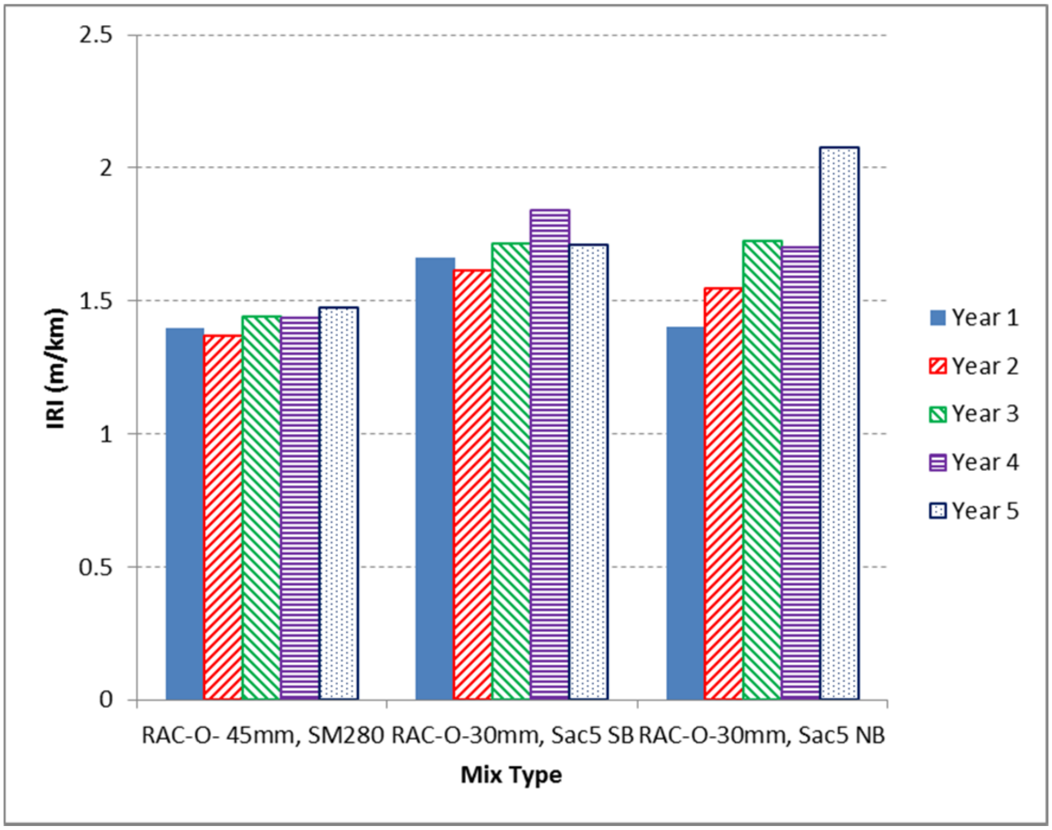


Figure A.31: Five-year IRI values for Sacramento 5 and San Mateo 280 sections. (Note: 1 m/km = 63 in./mi.)

Figure A.32 shows the five-year MPD values for the Sacramento 5 and San Mateo 280 sites. The fifth-year results show significantly increased MPD values for the northbound direction, probably due to higher air-void content and more raveling. The increase in MPD values of Sacramento 5 SB from year four to year five is not statistically significant. The MPD value of San Mateo 280 significantly decreased from year four to year five. This might have happened due to an increase in bleeding.

Figure A.33 shows the five-year overall sound intensity levels for the Sacramento 5 and San Mateo 280 sections. According to the figure, the northbound section of the Sacramento 5 site exhibited a major increase in noise level from year four to year five—98.2 dB(A) to 103.2 dB(A). This observation conforms to the increase in the values of IRI and MPD from year four to year five. The sound intensity spectra revealed that in the fifth year the noise levels in low-frequency bands (500, 630, and 800 Hz) were significantly higher than those in the fourth year. This indicates that in the fifth year the pavement surface experienced a significant change in surface distresses that resulted in more tire vibration and low-frequency noise. The overall sound intensity for the San Mateo 280 sections increased slightly from year four to five. The overall sound intensity for the Sacramento 5 sections decreased about 1 dB(A) from year four to year five, and the reason is unknown.

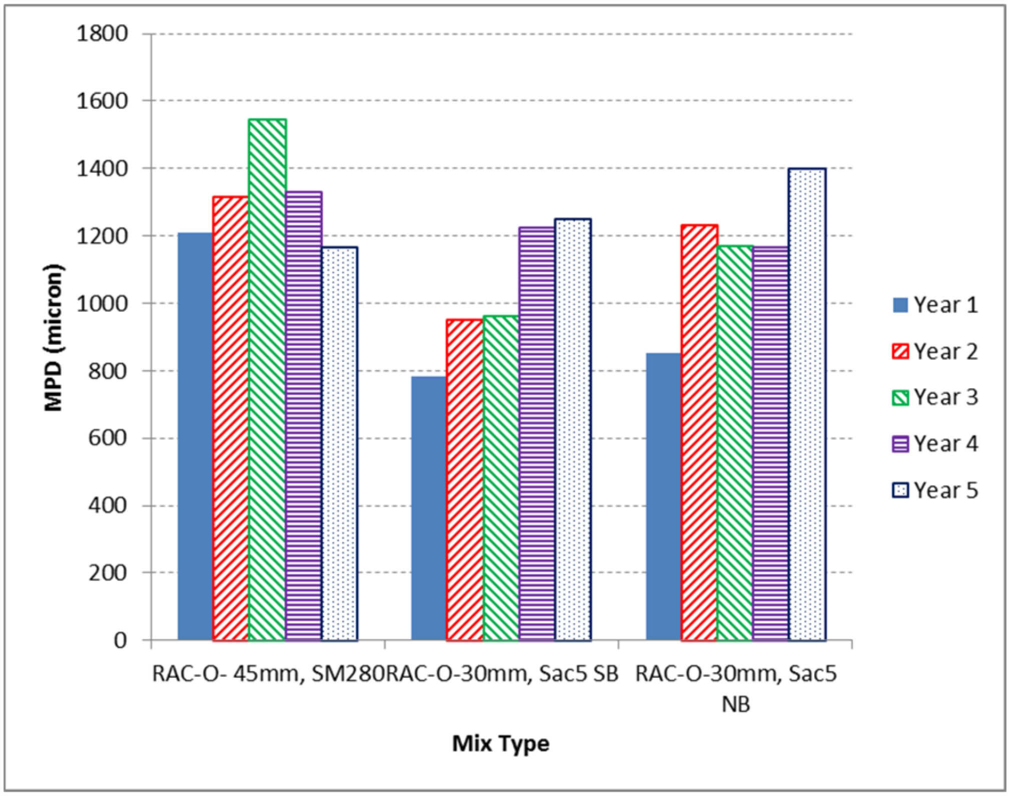


Figure A.32 Five-year MPD values for Sacramento 5 and San Mateo 280 sections.

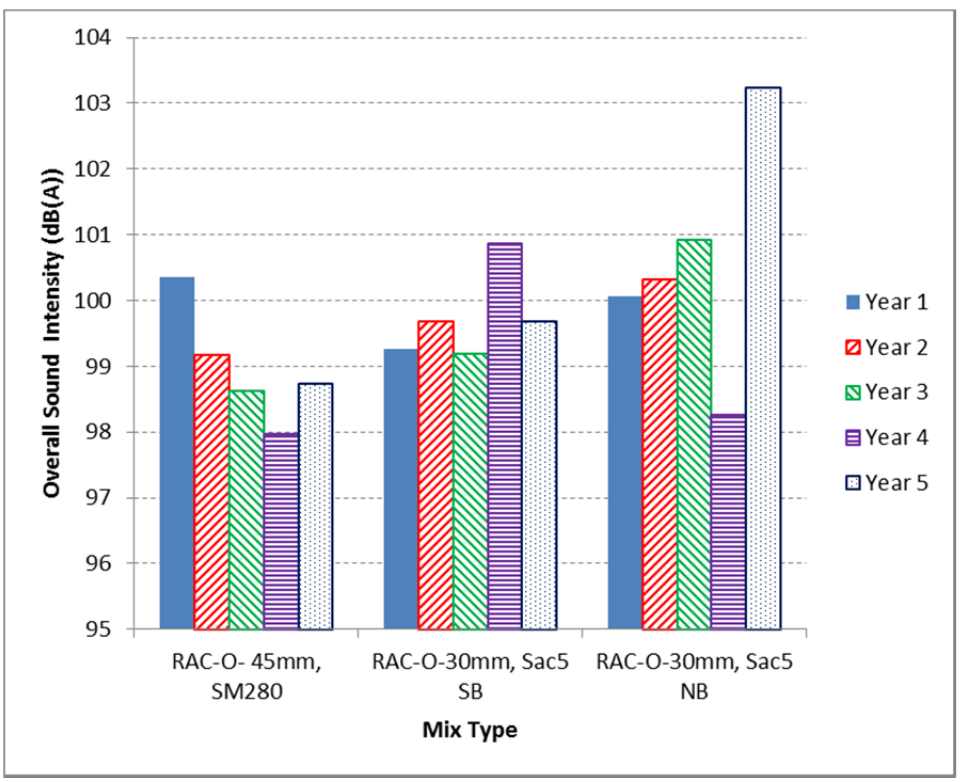


Figure A.33: Five-year overall OBSI values for Sacramento 5 and San Mateo 280 sections.

Overall, the San Mateo 280 section performed better than the Sacramento 5 sections in terms of both noise and IRI. The thicker overlay (45 mm instead of 30 mm) on the San Mateo 280 section and its lower truck traffic may have contributed to its better performance.

A.5.3 LA 138 Sections

The LA 138 site includes four mix types—OGAC, RAC-O, Bituminous Wearing Course (BWC), and DGAC—which were placed in both the eastbound and westbound lanes. Measurements were taken on the seven test sections: on the eastbound (EB) and westbound (WB) OGAC, RAC-O, and BWC sections and on the westbound DGAC mix. All the mixes have an NMAS of 12.5 mm. The test sections were three years old during the first-year measurements. OGAC was placed in 75- and 30-mm thicknesses in different sections to determine the effect of thickness on noise and roughness. All other sections were placed at a thickness of 30 mm.

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

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

The analysis of the first two years of data revealed that most of the LA 138 open-graded mixes have much lower than typical air-void contents. The permeability of these OGAC and RAC-O mixes is also lower than the average permeability of other OGAC and RAC-O mixes in the same age category. The eastbound sections have 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.34 shows the five-year IRI values for the LA 138 sections. As with the fourth-year data, the RAC-O mixes have the lowest IRI values in the fifth year as well. In the first year of measurements, all 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).* There was a slight change in IRI from year four to year five, but for the most part the change is not significant.

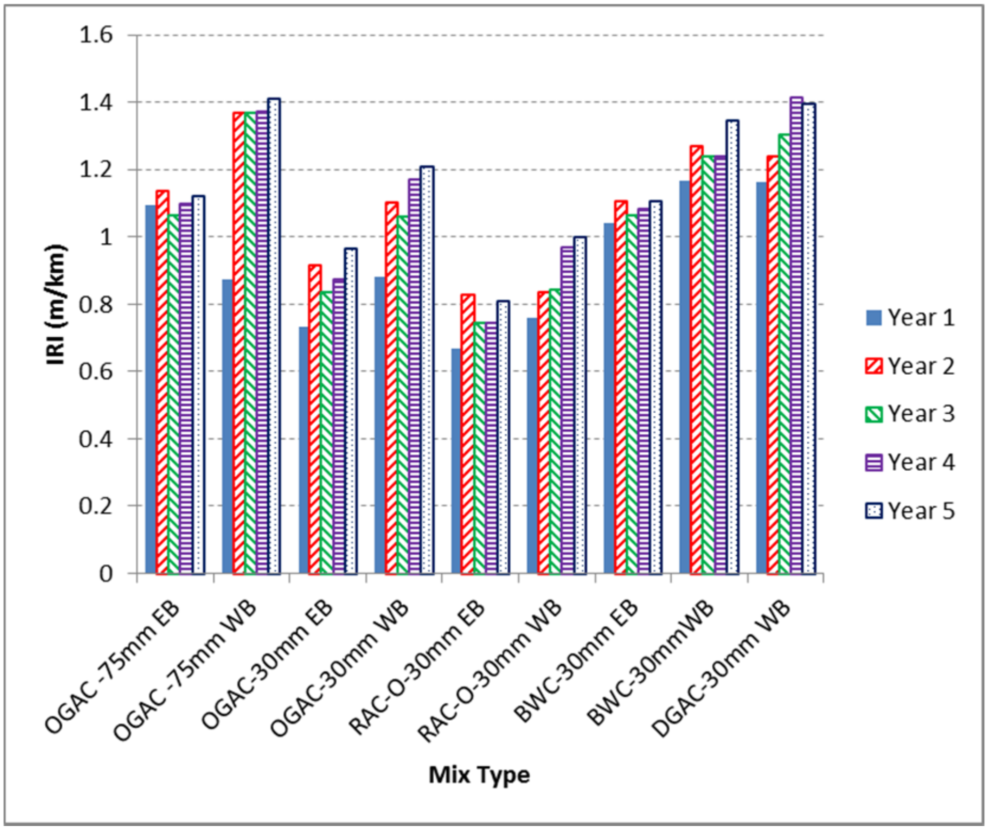


Figure A.34: Five-year IRI values for the LA 138 sections.

The third-year MPD was not measured on the LA 138 sections. Based on the previous two years of measurement, as shown in Figure A.35, it was found that open-graded mixes had higher MPD values than the BWC and dense-graded mixes (*1, 6*). RAC-O mixes exhibited the smallest MPD values among all open-graded mixes. MPD decreased in the fifth year significantly for all sections. The reason for a decrease in the value of MPD from year four to five is unknown. There seems to be no interaction between layer thickness and the change in the MPD.

Figure A.36 shows the five-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 are not included *(1, 6)*. Although in the fifth year of data collection open-graded mixes including OGAC 30 mm and OGAC 75 mm exhibit a significant increase in the overall sound intensity level between 2 to 3 dB(A), they still have the lowest overall sound intensity level. BWC and DGAC sections experienced less variation in noise level from year four to year five but are the noisiest sections with a measured overall sound intensity of about 103 dB(A). The sound intensity spectra revealed that in the fifth year, the noise levels in high frequency bands (1,000 Hz to 5,000 Hz) were significantly higher than those in the fourth year. This indicates that the pavement surface in the fifth year experienced a significant change in air-void content that resulted in more noise due to air pumping.

There seems to be no interaction between surface layer thickness and overall sound intensity.

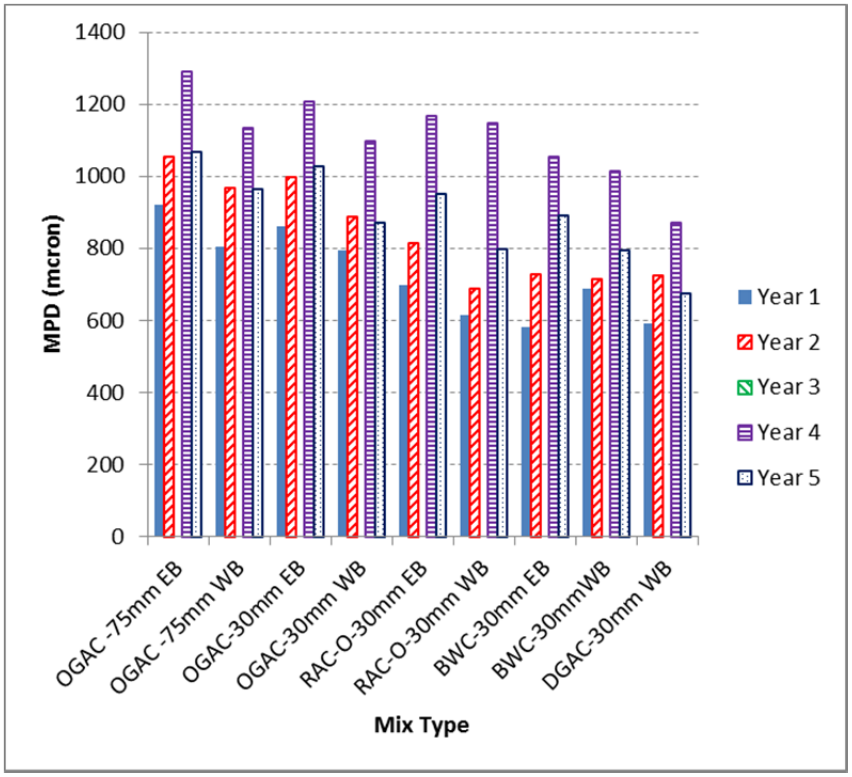


Figure A.35: Five-year MPD values for the LA 138 sections.

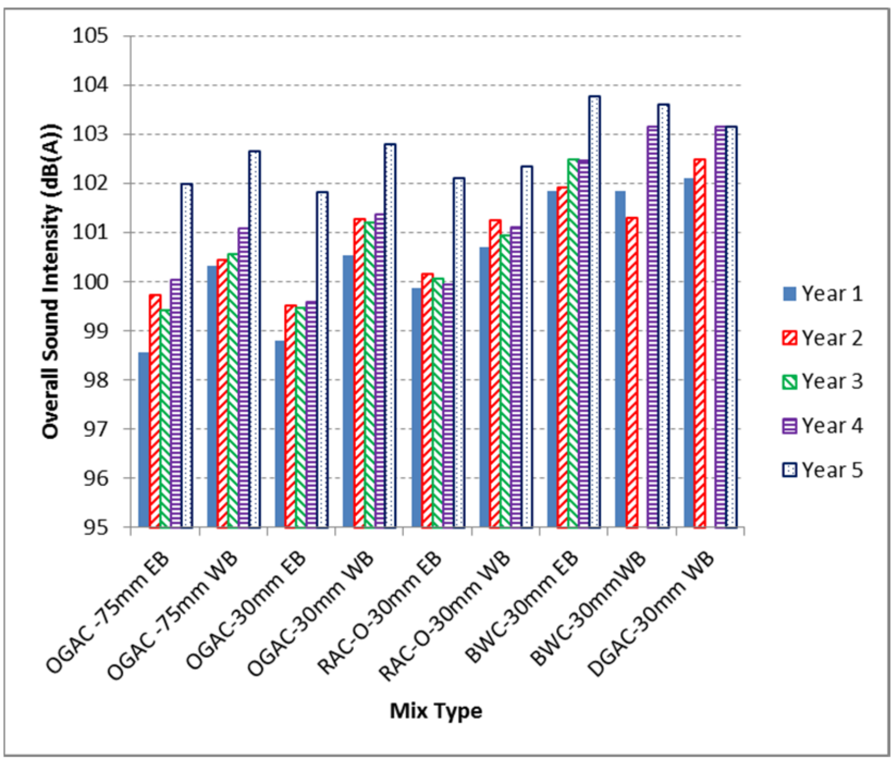


Figure A.36: Five-year overall OBSI values for LA 138 sections.

In summary, OGAC, mixes have the lowest noise levels among all the mix types in the five survey years, yet they exhibit the largest variation in the noise level. BWC mixes have noise performance closer to that of the DGAC mixes than to the open-graded mixes.

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).*

The first two years of data showed that that EU-GG retains its permeability longer than Caltrans RAC-G mixes *(1,6).* Figure A.37 shows the five-year IRI values for the LA 19 section. It can be seen that the IRI on the EU-GG mix has not changed significantly with pavement age over the five survey years, and even decreased in the fifth survey year. This mix provides a good smoothness for interstate highways, according to the FHWA criterion (less than 1.50 m/km [95 in./mi]) *(1).*

Figure A.38 shows the five-year MPD values for the LA 19 section. The MPD on the EU-GG increased slightly from the second to the fifth survey year. Figure A.39 shows the overall OBSI measured in five years on the LA 19 section. *(Note*: The third year data is missing.) It can be seen from the plot that the overall sound intensity of the EU-GG mix did not significantly increase over the five years of data collection. Moreover, the EU-GG mix can provide a reasonably quiet pavement for interstate highways, and it does not lose it its noise-reducing ability over time.

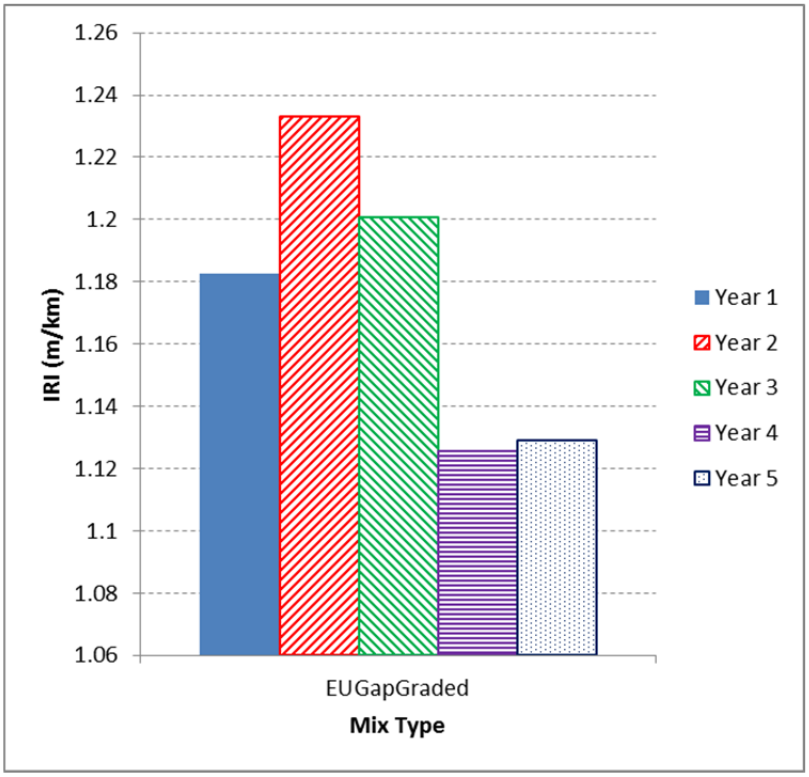


Figure A.37: Five-year IRI values for the LA 19 section.

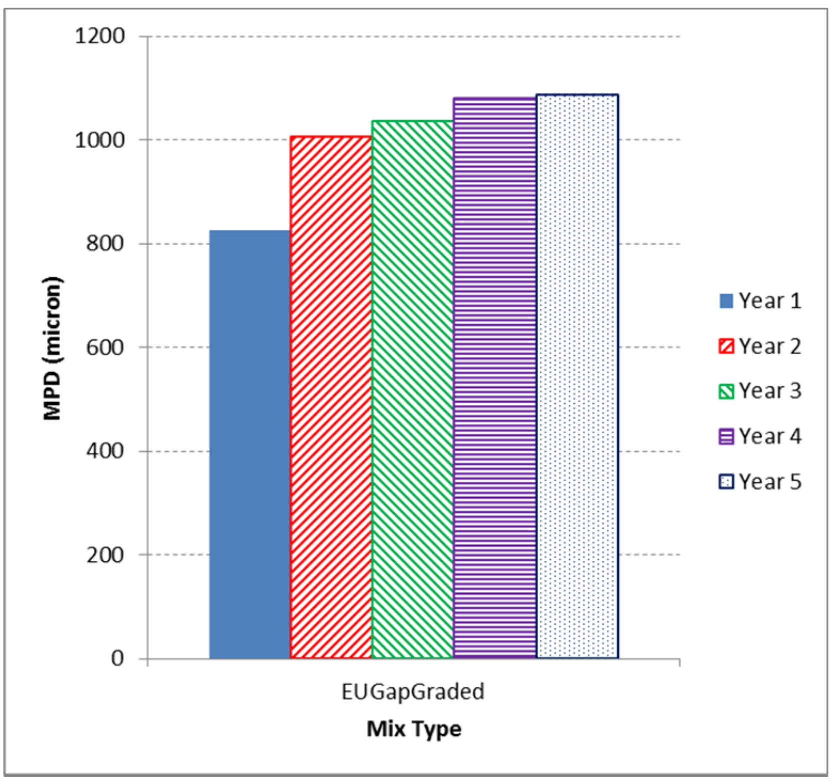


Figure A.38: Five-year MPD values for the LA 19 section.

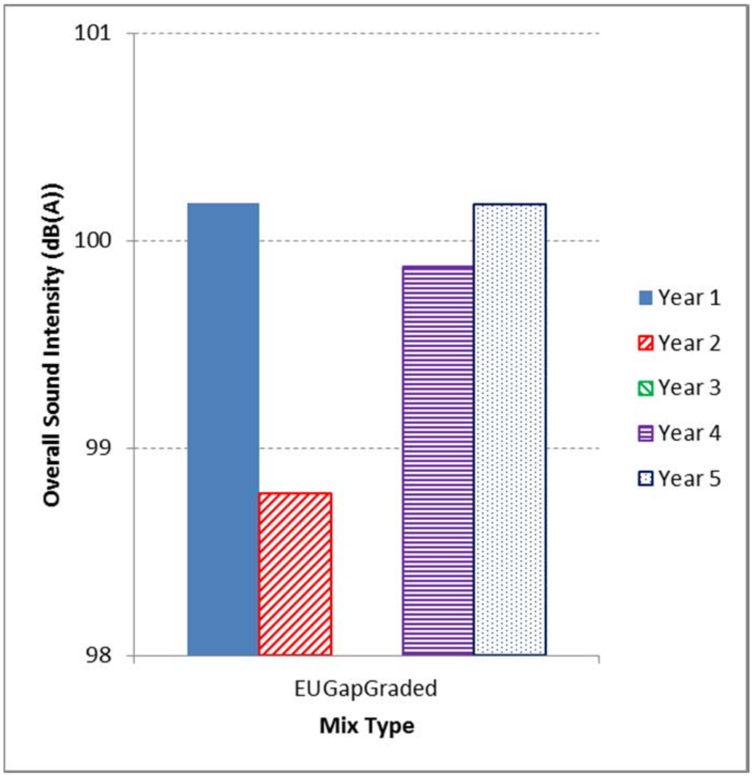


Figure A.39: Five-year overall OBSI values for the LA 19 section.

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 has higher air-void content but lower permeability than the average OGAC mix *(1).*

Figure A.40 shows the five-year IRI values for the Yolo 80 section. The figure shows that the IRI values increased slightly from the second to the third year and remained constant in the next three following years. Overall the section has good ride quality over the five survey years and can provide a good smoothness for interstate highways according to the FHWA guideline (less than 1.50 m/km [95 in./mi]) *(1).*

Figure A.41 shows the five-year MPD values for the Yolo 80 section. After an initial increase in MPD values it remained constant over the next three years. The increases in MPD in the second and fifth year are probably due to increased raveling on the pavement surface.

Figure A.42 shows the five-year overall noise levels for the Yolo 80 section. It can be seen that this section had an overall sound intensity from between 102 dB(A) and 103 dB(A) in the first two years which increased to slightly over 105 dB(A) by the fifth year. The noise spectra of this section shows that the increase of noise mainly occurred at frequencies lower than 1,000 Hz. This indicates that the increase of noise was probably caused by increased raveling. This results corresponds to the change in MPD value shown in Figure A.41.

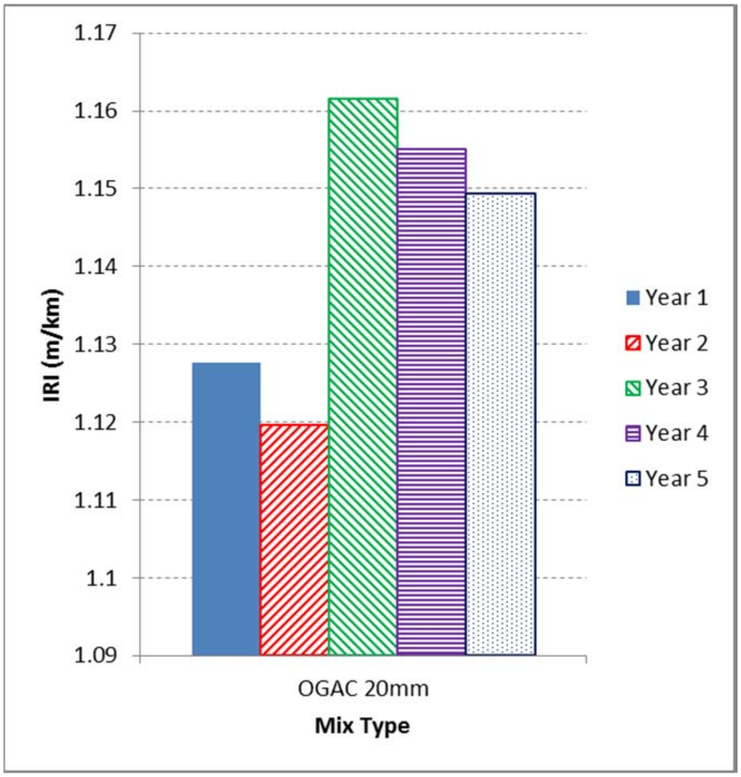


Figure A.40: Five-year IRI values for the Yolo 80 section.

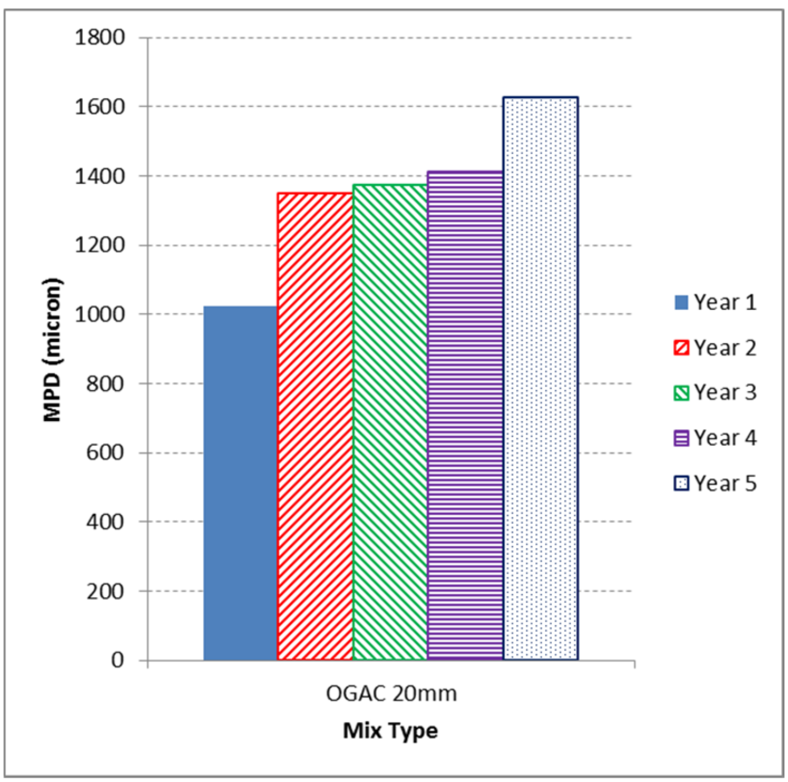


Figure A.41: Five-year MPD values for the Yolo 80 section.

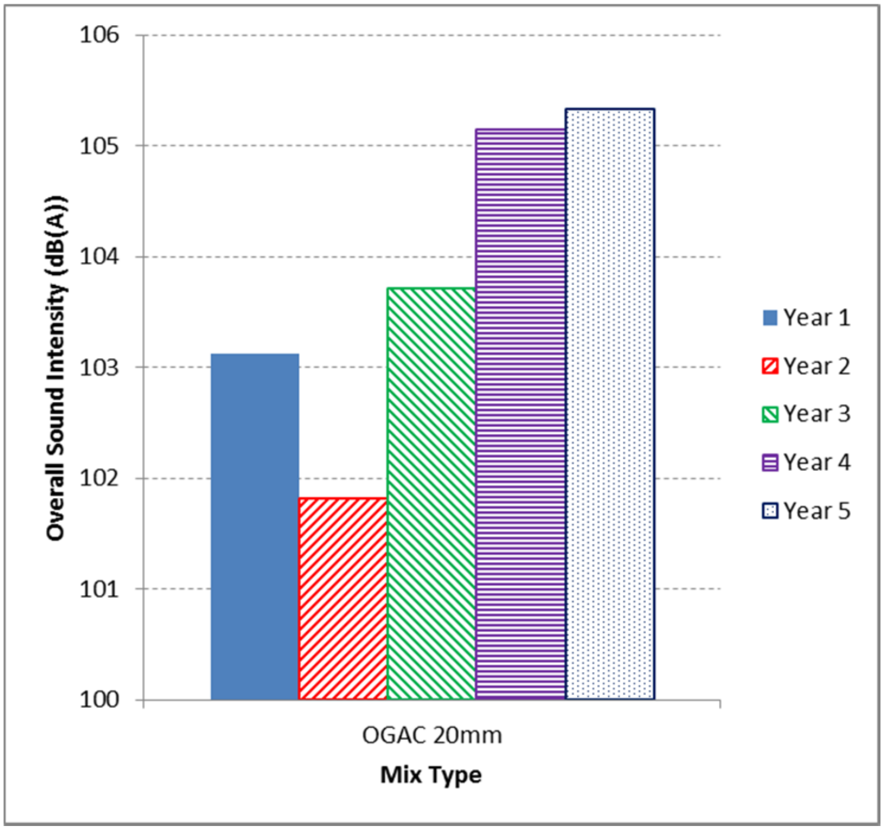


Figure A.42: Five-year overall OBSI values for the Yolo 80 section.

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 and loses its noise-reducing capability over the years due to increases in surface roughness.

A.5.6 BWC Sections

To provide additional data regarding BWC, a set of eight sections at five different locations were tested by the UCPRC car in July 2007 and again in June 2011. These sections were identified by industry as being "more representative" of BWC than the BWC placed on the LA 138 section discussed in Section A.6.3 of this report, which showed no noise advantages compared to DGAC.

The test speed was 60 mph (97 km/h) except on Section BWC-01 where the speed was 35 mph (56 km/h). This section was subsequently dropped from experimental design. Table A.38 presents the locations of the eight pavement sections.

Table A.38: 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 the 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.39.

Table A.39: Physical Properties of BWC Sections from SemMaterial and 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 CA (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.43. Most of the sections exhibit an increase of 2 dB(A) over a four-year measurement interval, which is quite acceptable, except for the BWC-04-N and BWC-04-S sections. These two sections showed significantly higher OBSI values of about 6 dB(A) after four years. Looking at the mean profile measured for BWC sections shown in Figure A.44, one might guess that raveling due to moisture damage might have caused these two BWC sections to exhibit such a significant increase in overall sound intensity. Although the same might be true for Section BWC-02, such an increase is not observed for those two sections. The other reason for a significant increase in the noise level for BWC-04–N and BWC-04-S might be clogging, during which the pores of the asphalt pavement are filled and the pavement loses its noise-reducing capabilities.

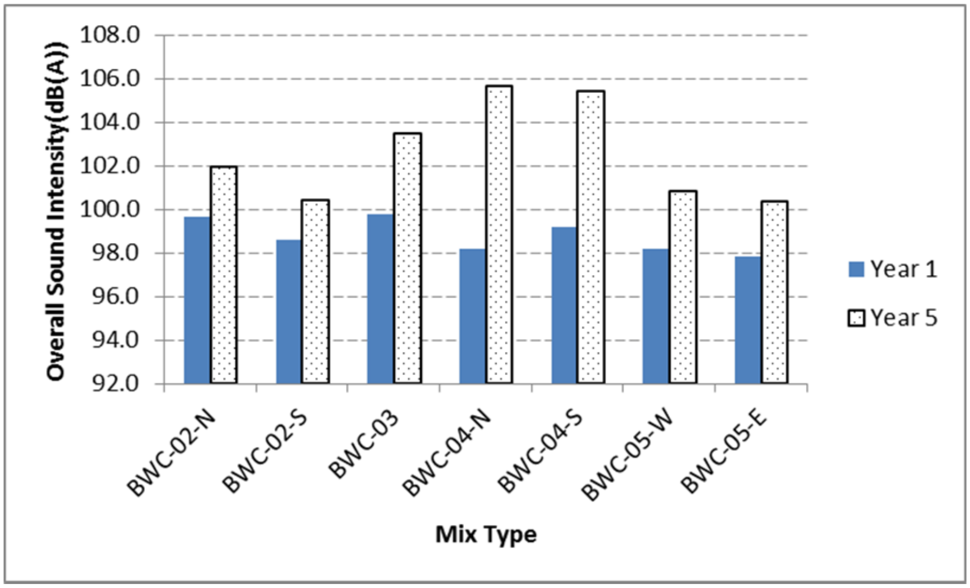


Figure A.43: Overall sound intensity levels for BWC sections.

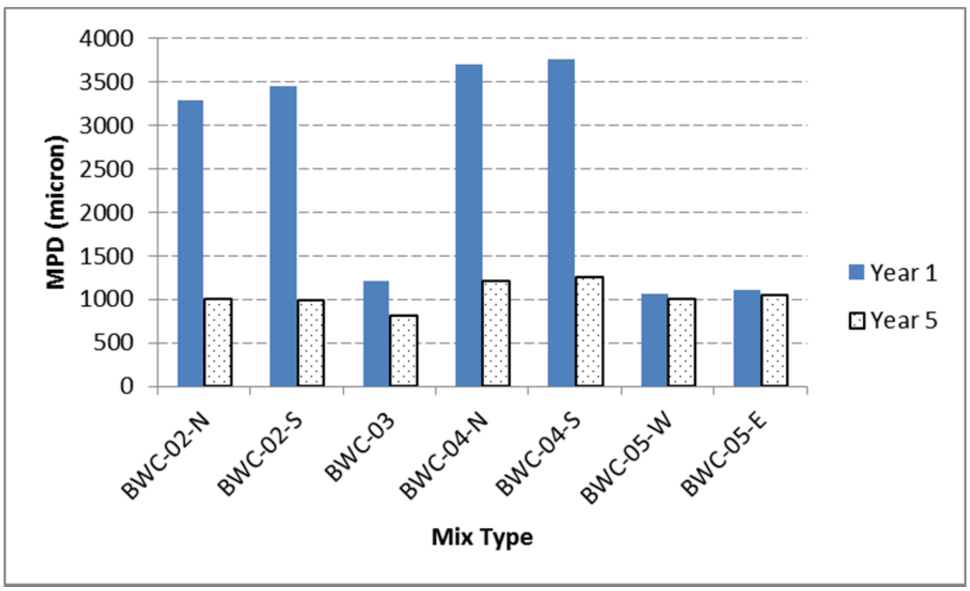


Figure A.44: Mean profile depth for BWC sections.

Figure A.45 and Figure A.46 compare the OBSI levels of these BWC sections with the QP and ES pavement sections measured in the first and second phases of data collection in 2007 and 2011. As shown in these two figures, compared to their DGAC counterparts, BWC sections in the first round of measurements exhibited a significantly lower overall sound intensity level. However, in the second round of measurements in 2011, only polymer-modified gap-graded sections were able to maintain their noise benefit, and sections with rubberized open-graded and polymer-modified open-graded mixes lost their advantage.

International Roughness Index (IRI) was obtained from elevation profiles measured on both wheelpaths. The results for each section are shown in Figure A.47. The right wheelpath was 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 sections over four years was not significant. All the BWC sections except for BWC-04-S can be used for interstate highways and provide good ride quality, according to FHWA guidelines.

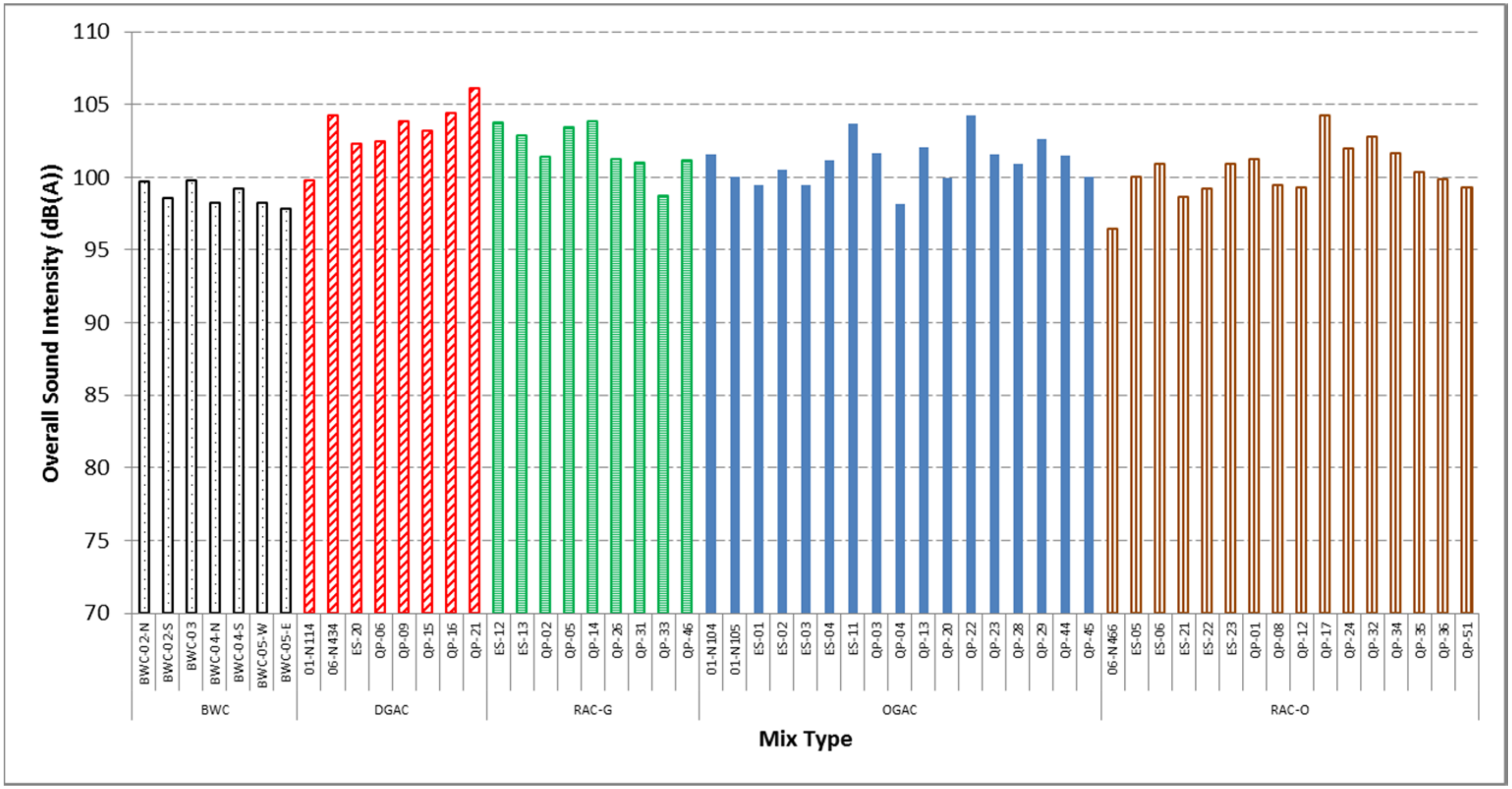


Figure A.45: Sound intensity levels of BWC compared to other pavement types, first round of measurements, 2007.

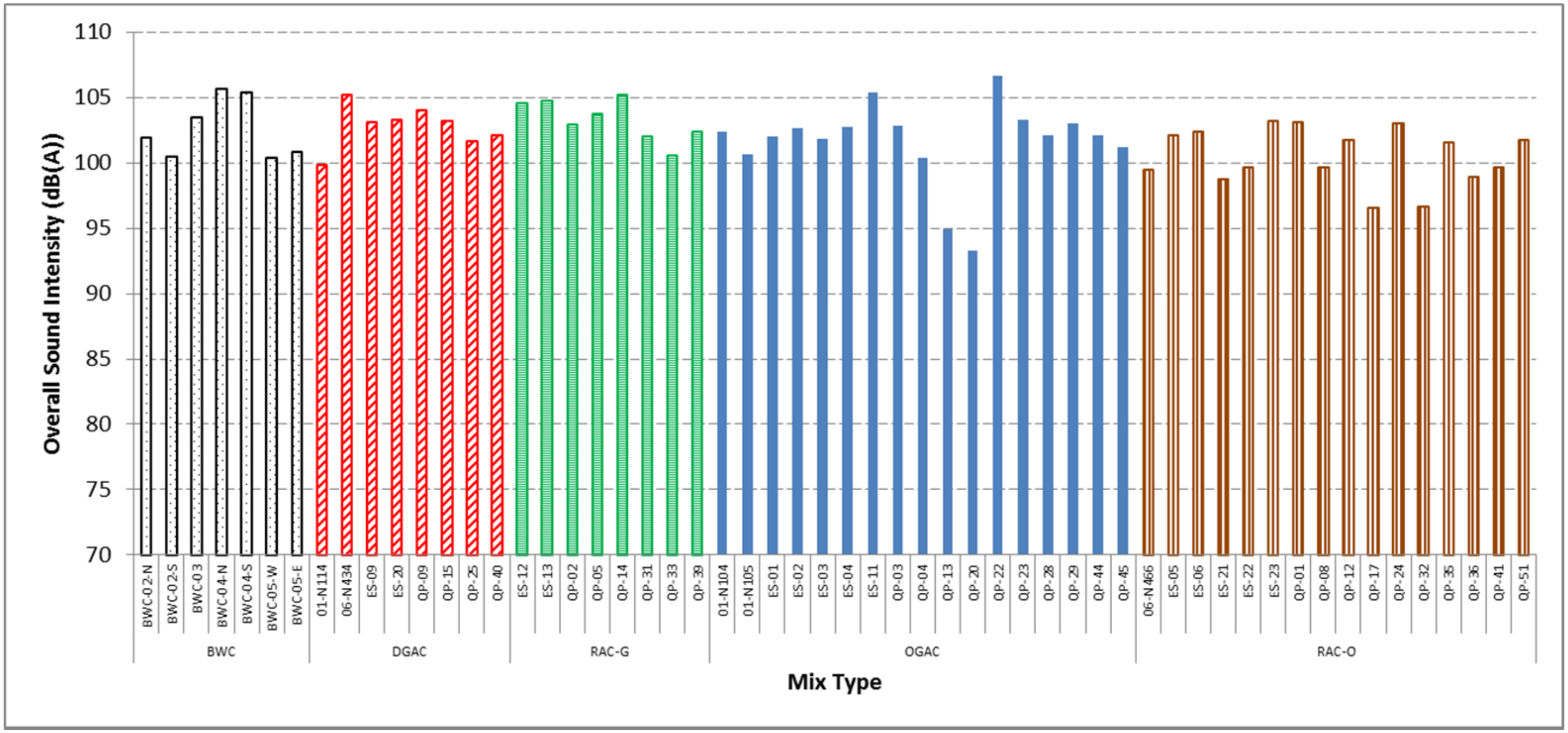
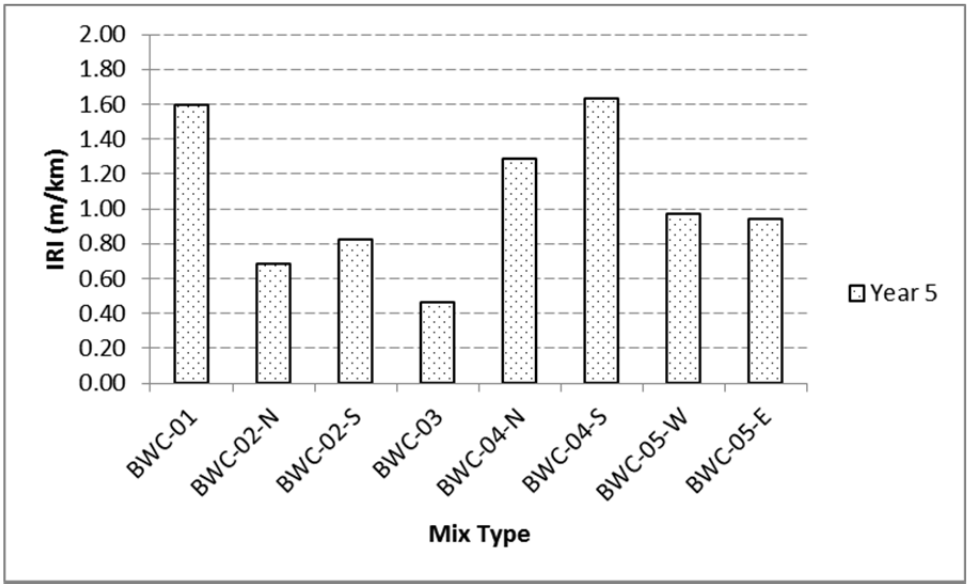
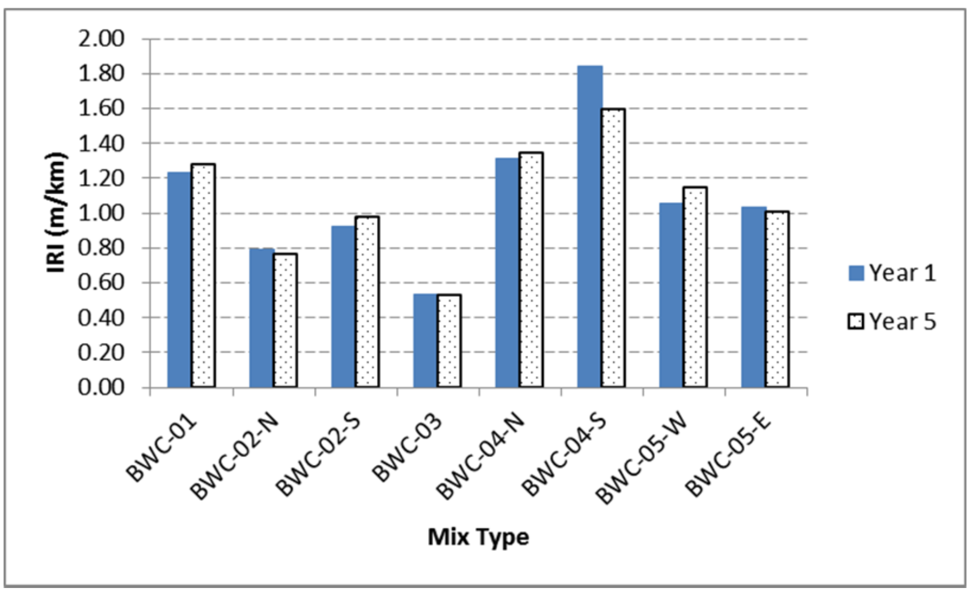


Figure A.46: Sound intensity levels of BWC compared to other pavement types, second round of measurements, 2011.



(a)



(b)

Figure A.47: IRI level for each BWC section: (a) right wheelpath, (b) left wheelpath.

A.5.7 Summary

The following observations were obtained from the environmental noise monitoring site (ES) sections:

- Based on the Fresno 33 sections, RAC-G and Type G-MB mixes generally exhibit the highest and lowest MPD values, respectively. RAC-G and RUMAC-GG exhibit higher IRI values than Type G-MB, Type D-MB, and DGAC mixes. There is no indication of the effect of layer thickness on the measures IRI and MPD. Tire/pavement noise increased significantly in the fifth survey year on the RAC-G 45 mm, DGAC, and RUMAC-GG 45 mm. RAC-G 45 mm mixes exhibit the highest noise level with 104.7 dB(A) and the Type G 45 mm mixes exhibit the lowest noise intensity, with a value of 102.7 dB(A). None of these mixes can provide any noise reduction compared to the DGAC mix over the long run.

- The San Mateo 280 section performed better than the Sacramento 5 sections in terms of both noise and roughness, possibly due to its thicker layer. The RAC-O pavement placed on the Sacramento 5 northbound exhibited a major increase in IRI and noise in the fifth year of data collection due to its higher truck traffic.
- From the LA 138 test sections, it was found that RAC-O mixes have the highest IRI values. OGAC has the lowest noise levels among all the mix types over the five survey years, but exhibits a major increase in overall sound intensity. Performance of BWC mixes is more similar to DGAC mixes than to open-graded mixes. No interaction between noise-reducing properties and thickness was observed. The BWC mixes are not considered by industry to be representative of most BWC mixes in the state.
- The EU-GG mix performed relatively well in terms of providing sound-reducing benefits. The year-to-year increase in IRI for these mixes is not significant.
- The Yolo 80 section still provides good ride quality according to FHWA guidelines but has lost its noise-reducing capabilities.
- Almost all BWC sections provide good ride quality for interstate pavements.
- Polymer-modified open-graded BWC mixes rapidly lose their noise-reduction advantage, whereas polymer-modified gap-graded BWC mixes can maintain their noise-reduction advantage for a longer period.

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.1.1: 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 five 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 five 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 five 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 five 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	0
		1 to 4 years old	High	Low	01-MEN-101-50.8/ 51.5	QP-47	3	5,081	0
					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	0
					01-MEN-20-22.18 /22.68	QP-49	8	1,289	0

B.1.2: 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 0 0
Los Angeles 19 (LA 19)	07-LA-19/ PM 3.4	European gap-graded, 30 mm (ES-10)	May 2005	0
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	0 0 0 0 0 0 0 0 0
San Mateo 280 (SM 280)	04-SM-280/PM R0.0-R5.6	RAC-O, 45 mm (ES-21)	Fall 2002	0
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	0

***** Note:
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 five 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, the use of a particular test tire and/or sound analyzer, equipment, and pavement temperature on the On-board Sound Intensity (OBSI) measured near the tire/pavement interface, two factorial experiments were conducted on several pavement sections around Los Angeles and Davis, California, during May and June 2010.

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 equipment (Larson Davis, Harmonie), and pavement temperature (low [early morning], high [noon]). During this first set of tests, pavement temperature 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.1.2) 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]). Pavement temperature among all the measurements varied between 13°C and 52°C. The same sound analyzer equipment, Harmonie was used for all measurements.

Results of the above two factorial experiments were analyzed and applied to the fifth-year sound intensity data to convert them to reference conditions. 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 among the different SRTT tires that had been used in the UCPRC noise studies. Four tires (SRTT#A, SRTT#B, SRTT#3, and SRTT#4) were included in these experiments, which were conducted on both asphalt and concrete pavements. The tires named SRTT#A and SRTT#B in year two 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.

Table B.2.1 summarizes the experiments undertaken to develop calibration equations. In this table, the first two experiments are the two factorial experiments: Experiment numbers 1 and 2. Experiments 3 through 5 were added for calibration among the various SRTT tires, and experiments 6 through 9 were added for calibration between the Larson Davis and Harmonie analyzers.

Table B.2.1: 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	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
7	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
8	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.
9	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.2.2. As can be seen, the interactions between equipment and other variables (speed, tire, and pavement temperature) are generally insignificant for OBSI at all one-third octave frequency bands except for the 4,000 Hz and 5,000 Hz frequency 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.2.3. The estimated parameters (coefficients) in Table B.2.2 and Table B.2.3 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.2.2a shows that the Harmonie analyzer always gives a value -2.240157 dB(A) 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 to calibrate 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 25ºC 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.2.4. Figure B.2.1 shows the 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.2.4.

4. Calibrate for test vehicle speed using the parameters in Table B.2.5.
5. Calibrate for pavement temperature using the parameters in Table B.2.6.

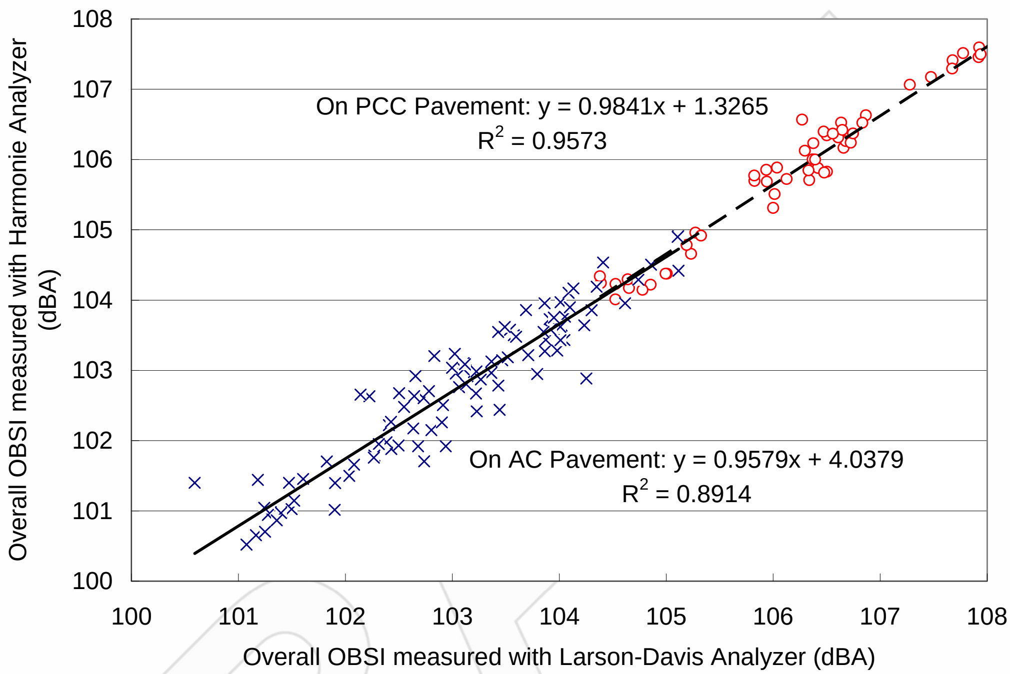


Figure B.2.1: Comparison of overall OBSI values measured with Larson Davis analyzer and Harmonie analyzer on AC and PCC Pavements.

Table B.2.2a: Regression Estimation Results for 400Hz-800Hz 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.2.2b: 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.2.2c: Regression Estimation Results for 2,500Hz – 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.2.2d: 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:

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

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.2.3a: 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:

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

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.2.3b: 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:

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

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.2.3c: 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:

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

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.2.3d: 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:

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

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.2.4: 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.2.5a: 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.2.5b: 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.2.6: 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 5 in Table B.2.1 were conducted to investigate the relationship between the four SRTT tires (SRTT#A [#1], SRTT#B [#2], SRTT#3, and SRTT#4). 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, and SRTT#3 and SRTT#4 were used in the fifth year data collection on AC pavements. SRTT#2, SRTT#3, and SRTT#4 were also used to collect the OBSI data on PCC pavements in the first, second, and third years, respectively. Experiments 3 through 5 included both AC and PCC sections, and used only the Harmonie analyzer to process noise data. Figure B.2.2 and Figure B.2.3 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.2.7a and b, respectively.

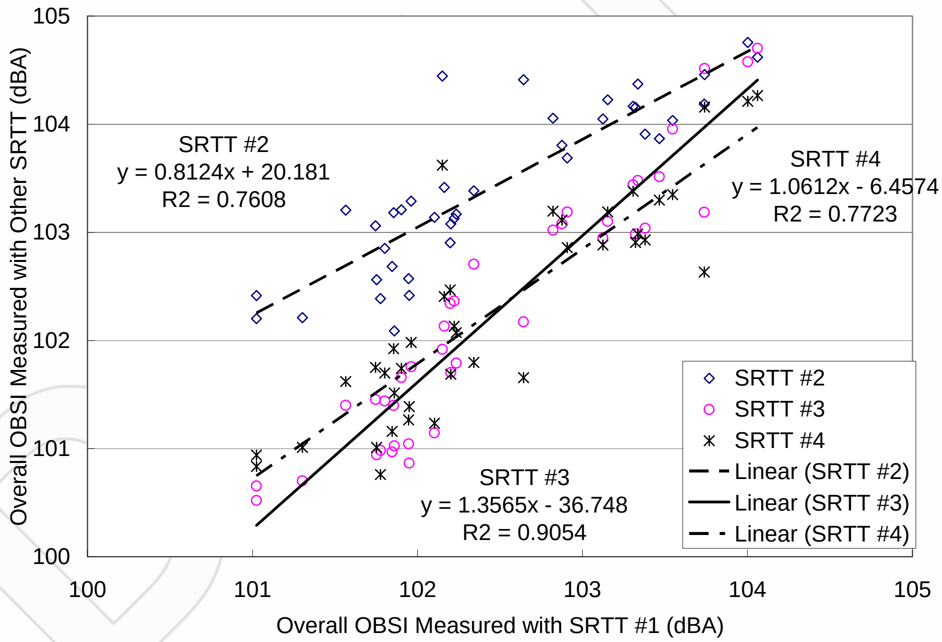


Figure B.2.2: Comparison of overall OBSI measured with various SRTT tires on AC pavements.

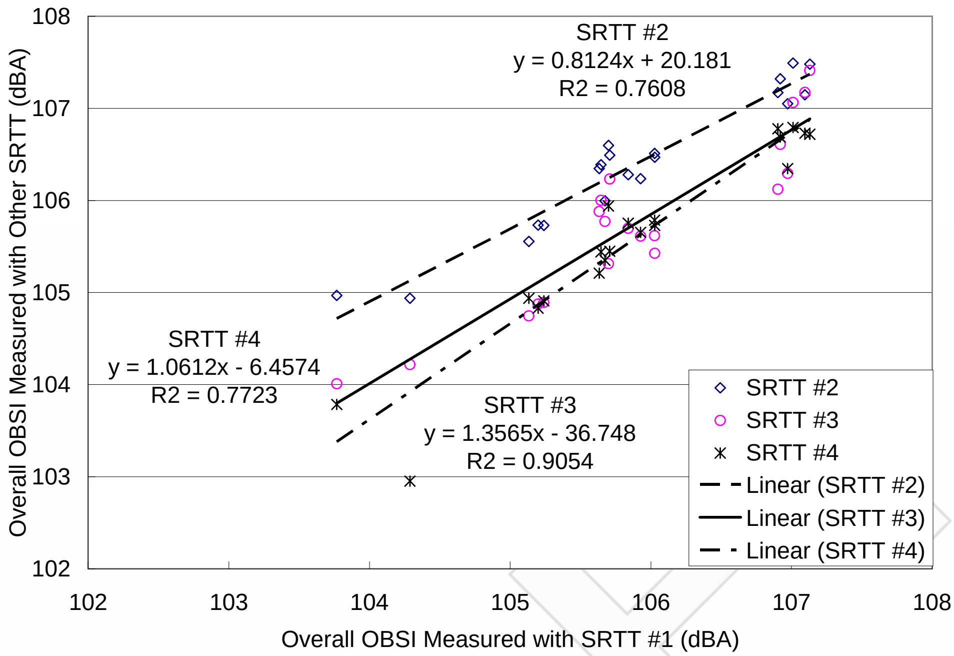


Figure B.2.3: Comparison of overall OBSI measured with various SRTT tires on PCC pavements.

Table B.2.7a: SRTT Tire Calibration Parameters on AC Pavements

	SRTT#1 to SRTT#3			SRTT#2 to SRTT#3		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	60.7380	0.2636	0.08	66.5322	0.1959	0.04
500	3.6808	0.9528	0.64	22.2986	0.7327	0.36
630	-0.8985	1.0042	0.76	2.0400	0.9682	0.52
800	-21.9632	1.2231	0.90	-22.5924	1.2230	0.75
1,000	-21.9966	1.2296	0.86	-18.6739	1.1755	0.64
1,250	-6.6236	1.0674	0.68	10.3488	0.8770	0.44
1,600	-44.2338	1.4727	0.93	-53.8537	1.5593	0.91
2,000	-30.5374	1.3346	0.93	-23.2965	1.2397	0.94
2,500	-31.8006	1.3660	0.83	-19.4132	1.2104	0.90
3,150	-32.1054	1.3894	0.77	-26.0760	1.3040	0.80
4,000	-31.8360	1.4004	0.84	-19.8023	1.2397	0.84
5,000	-35.0003	1.4565	0.86	-19.3382	1.2451	0.80
Overall	-36.7482	1.3565	0.91	-37.3630	1.3499	0.78
	SRTT#4 to SRTT#1			**SRTT#2 to SRTT#1**		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	1.165082	0.98492	0.82	25.2230	0.7044	0.50
500	-0.01887	1.000083	0.93	24.4337	0.7125	0.48
630	-3.38009	1.031952	0.91	14.8822	0.8323	0.51
800	2.748531	0.971176	0.94	6.0426	0.9328	0.73
1,000	9.352439	0.906898	0.92	-0.9962	0.9940	0.81
1,250	9.855945	0.902846	0.93	16.1836	0.8186	0.65
1,600	7.923541	0.921163	0.97	-2.4799	1.0157	0.90
2,000	-0.52355	1.013398	0.97	8.0316	0.9005	0.95
2,500	3.603458	0.961996	0.96	16.6884	0.7994	0.88
3,150	1.713244	0.979757	0.95	16.4124	0.7935	0.75
4,000	-0.16919	1.002853	0.96	16.9545	0.7799	0.78
5,000	0.705826	0.990318	0.94	17.4375	0.7670	0.75
Overall	4.126298	0.962289	0.96	5.6130	0.9365	0.76

Table B.2.7b: SRTT Tire Calibration Parameters on PCC Pavements

	SRTT#1 to SRTT#3			SRTT#2 to SRTT#3		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	-5.2795	1.0498	0.72	20.4138	0.7668	0.30
500	24.3890	0.7274	0.80	14.5457	0.8347	0.89
630	14.2176	0.8452	0.85	11.2100	0.8787	0.87
800	13.9783	0.8591	0.93	12.1956	0.8756	0.87
1,000	1.0015	0.9900	0.92	13.8438	0.8519	0.60
1,250	1.0296	0.9876	0.92	-0.2586	0.9924	0.93
1,600	-10.0633	1.1053	0.93	-17.2125	1.1725	0.94
2,000	-1.1616	1.0119	0.90	-13.8908	1.1358	0.95
2,500	-0.7452	1.0103	0.89	-3.6465	1.0320	0.92
3,150	-11.9573	1.1430	0.92	-17.8493	1.2046	0.95
4,000	-8.3923	1.1006	0.91	-12.4682	1.1471	0.94
5,000	-2.0791	1.0259	0.89	-6.1325	1.0781	0.93
Overall	8.5215	0.9182	0.85	-15.7817	1.1423	0.87
	SRTT#4 to SRTT#1			**SRTT#2 to SRTT#1**		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	7.9554	0.9083	0.89	12.9152	0.8641	0.58
500	12.6198	0.8596	0.93	-4.8252	1.0516	0.93
630	3.9940	0.9590	0.96	-0.1345	1.0032	0.96
800	1.6524	0.9834	0.95	-3.6086	1.0344	0.95
1,000	-8.0857	1.0788	0.83	12.8477	0.8618	0.65
1,250	3.4569	0.9580	0.90	2.3379	0.9677	0.94
1,600	-13.5713	1.1332	0.94	-3.6609	1.0318	0.95
2,000	-3.7569	1.0296	0.93	-6.1668	1.0549	0.93
2,500	-1.3425	1.0102	0.93	2.1505	0.9663	0.92
3,150	-4.4291	1.0487	0.96	-1.3482	1.0095	0.95
4,000	-4.1357	1.0461	0.97	-0.4646	1.0028	0.96
5,000	-4.0292	1.0471	0.94	0.9657	0.9886	0.92
Overall	-4.5093	1.0397	0.91	-20.5446	1.1884	0.94

Experiments 6 through 9 in Table B.2.1 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 the factorial experiments 1 and 2 in Table B.2.1. Simple linear regression analysis was conducted on the data from the four experiments. The results are summarized in Table B.2.8.

Table B.2.8 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

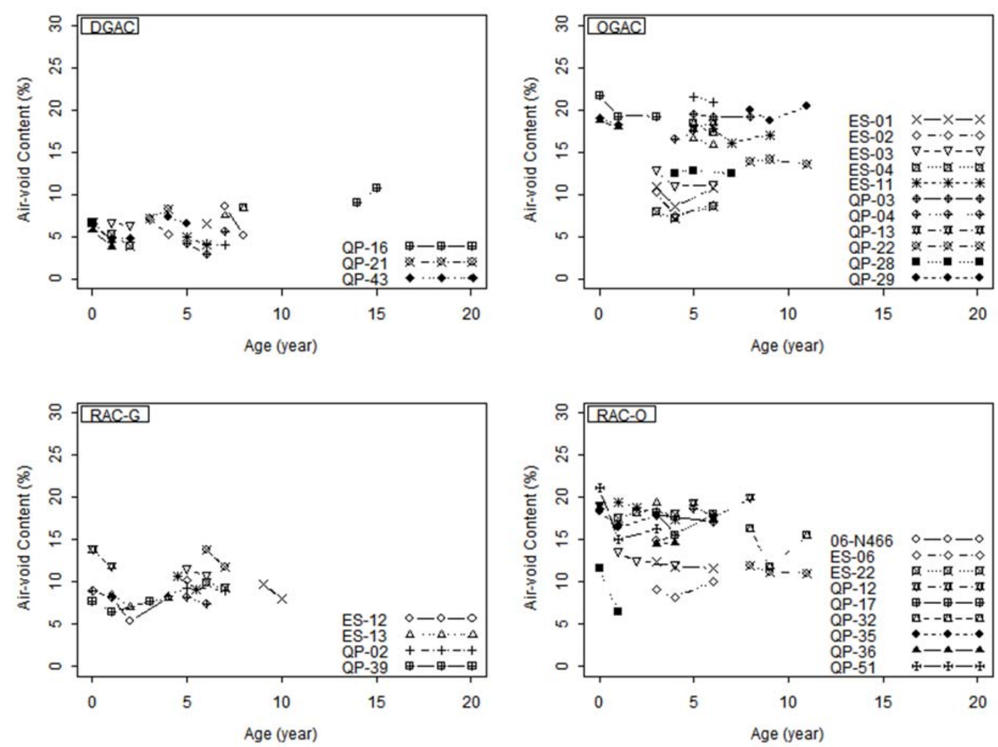
After reviewing the first five-year data analysis and the calibration equations developed in this section, Caltrans and UCPRC reached an agreement regarding how to handle the calibration of OBSI data for the five-year analysis report. It was agreed that UCPRC would take these steps in preparing the data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

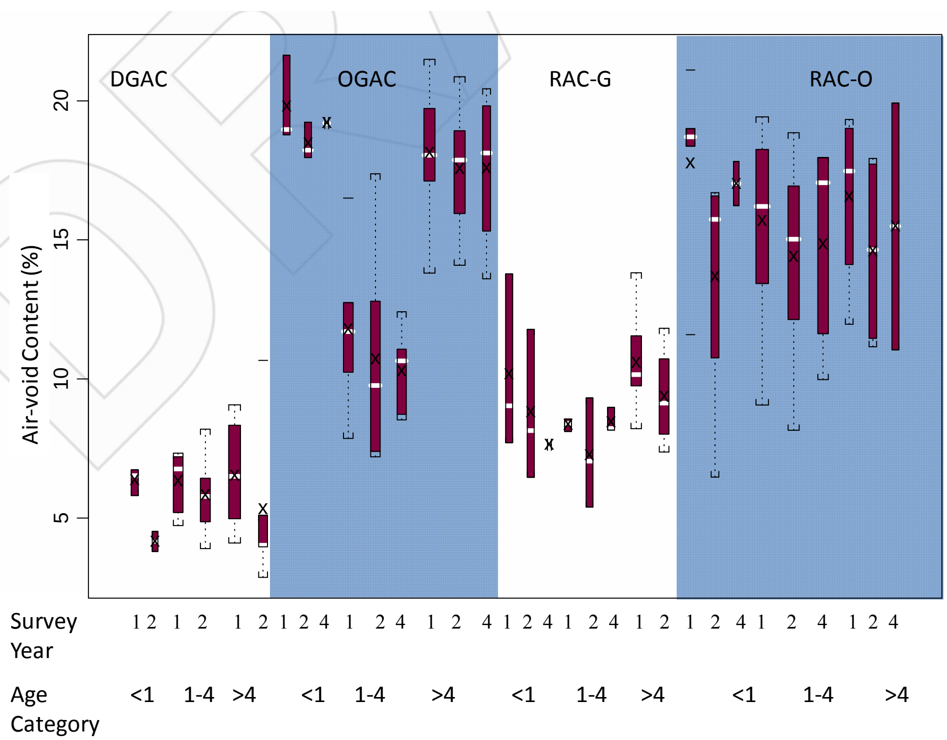
1. Disregard calibration for pavement temperature;
2. Remove all OBSI data measured at a test car speed other than 60 mph;
3. Calibrate the first three years of AC data from Larson Davis to Harmonie equipment using the parameters in Table B.2.6b;
4. Calibrate the fifth year data from SRTT#4 to SRTT#1 using parameters in Table B.2.7a;
5. Calibrate the fourth year data from SRTT#2 to SRTT#1 using parameters in Table B.2.7a;
6. 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;
7. 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.

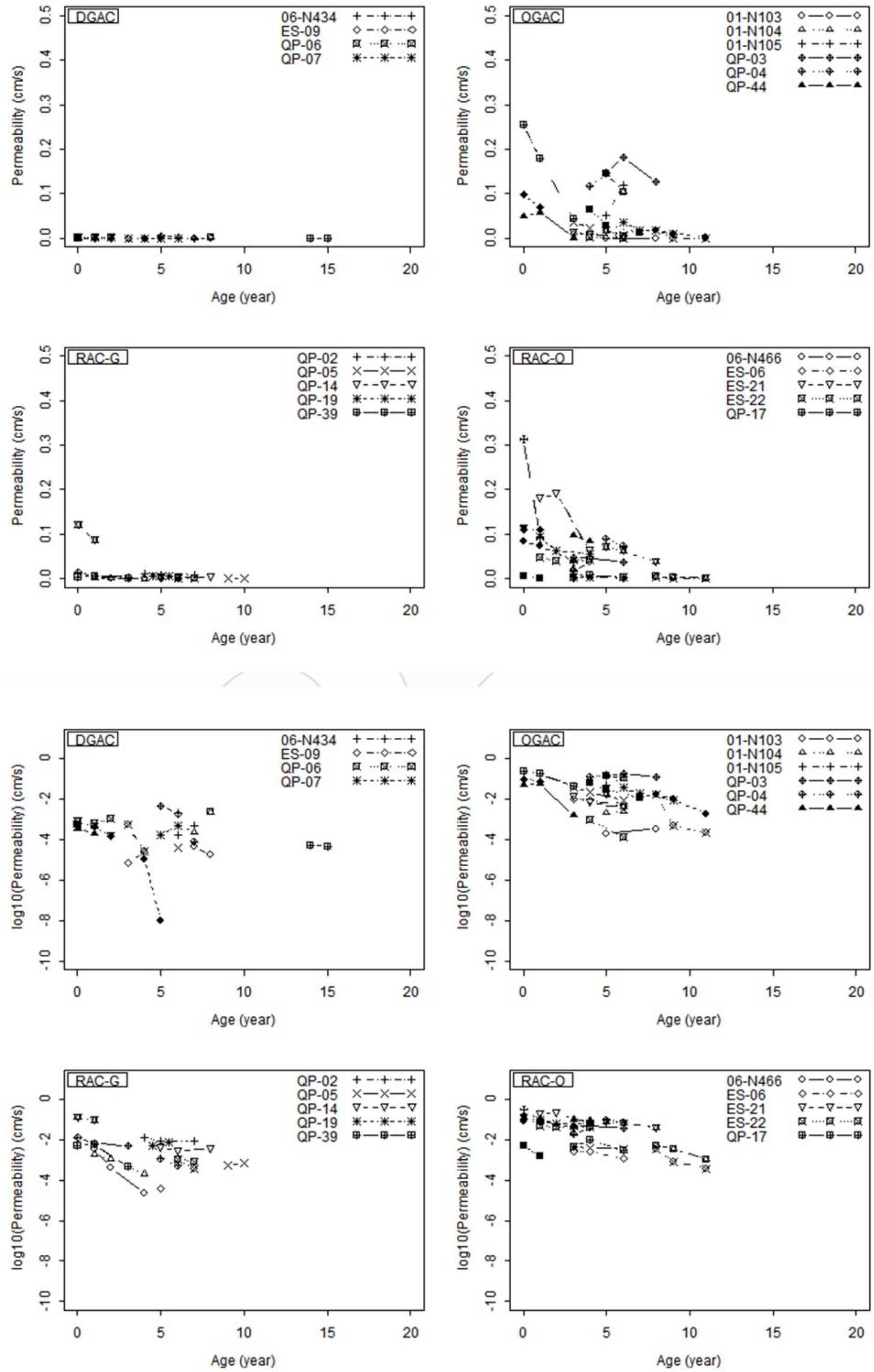
Appendix B.3: Plots of Air-Void Content and Permeability

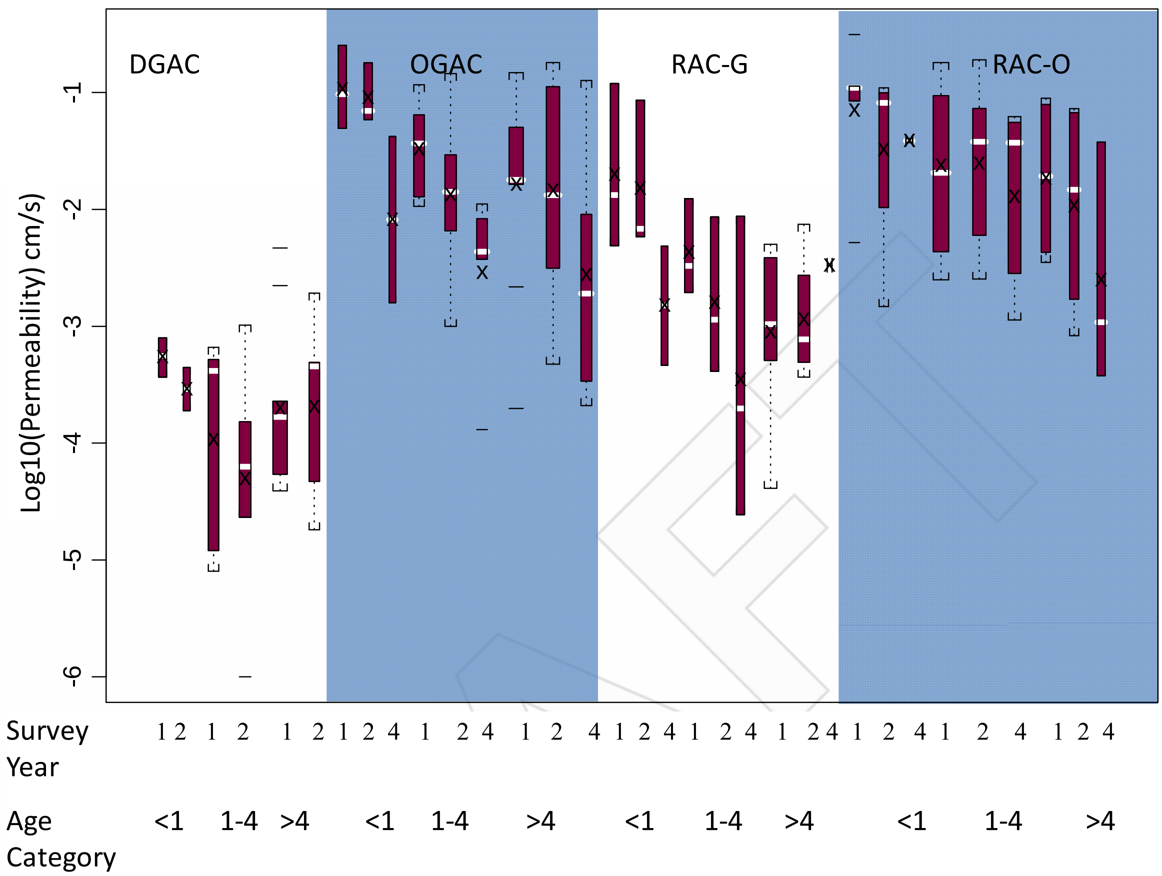
B.3.1 Trend Lines and Box Plots of Air-Void Content





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





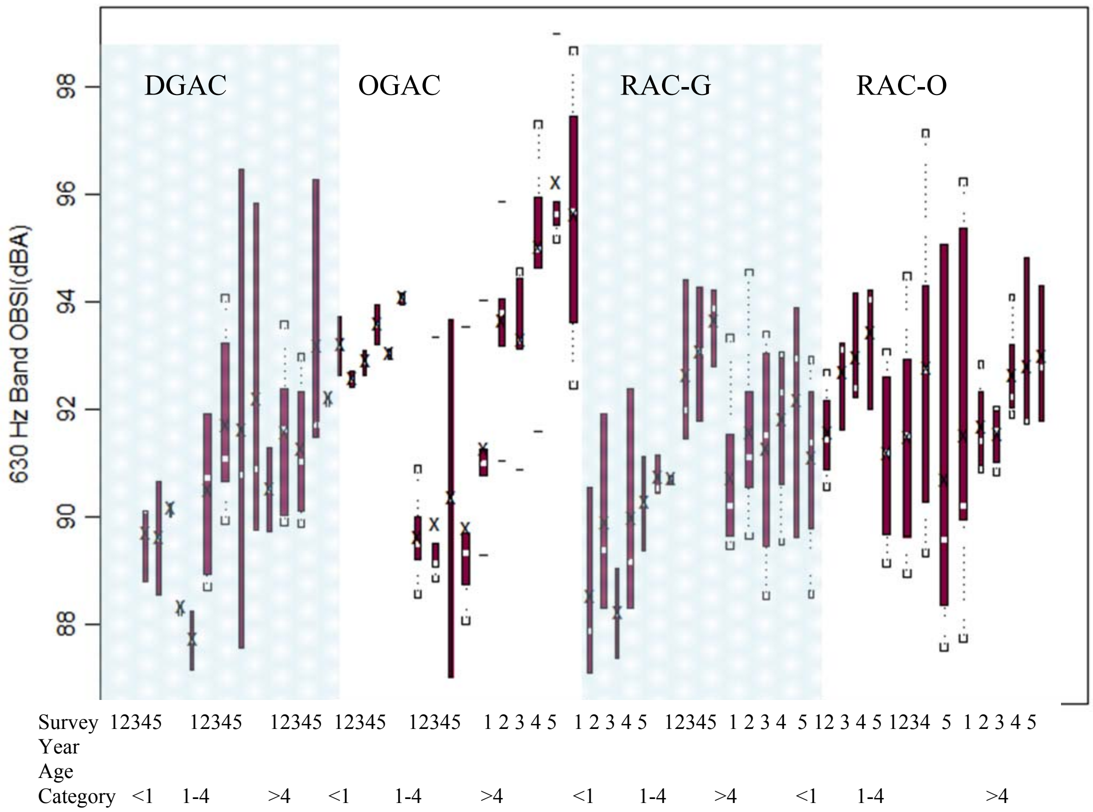
Multiple linear regression model:

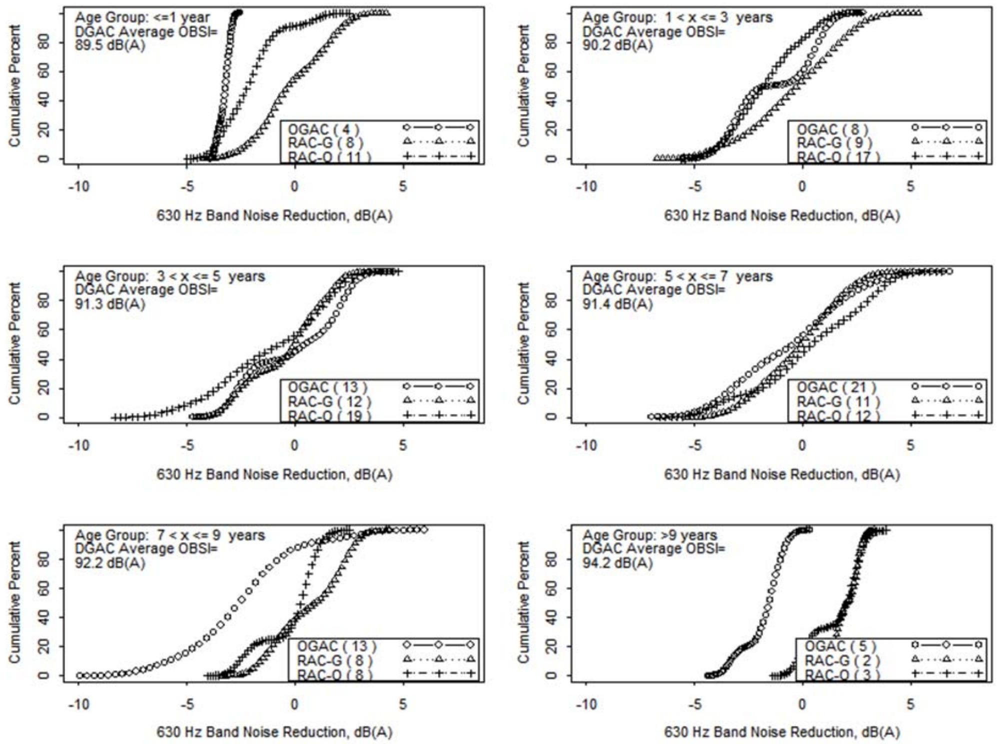
$$\log(Permeability[cm/s]) = -13.6863 - 0.2147 \times Age(year) + 1.4809 \times ind(OGAC) + 0.1943 \times ind(RAC-G) + 1.5398 \times ind(RAC-O) + 0.1696 \times AirVoid(\%) + 1.2788 \times FinenessModulus$$

	Value	Std. Error	t value	P-value
(Intercept)	-13.6863	1.9798	-6.9131	<0.0001
Age	-0.2147	0.0373	-5.7536	<0.0001
PvmntTypeOGAC	1.4809	0.5255	2.8182	0.0054
PvmntTypeRAC-G	0.1943	0.4708	0.4128	0.6802
PvmntTypeRAC-O	1.5398	0.5214	2.9530	0.0036
AirVoid	0.1696	0.0380	4.4575	<0.0001
FinenessModulus	1.2788	0.4703	2.7189	0.0072

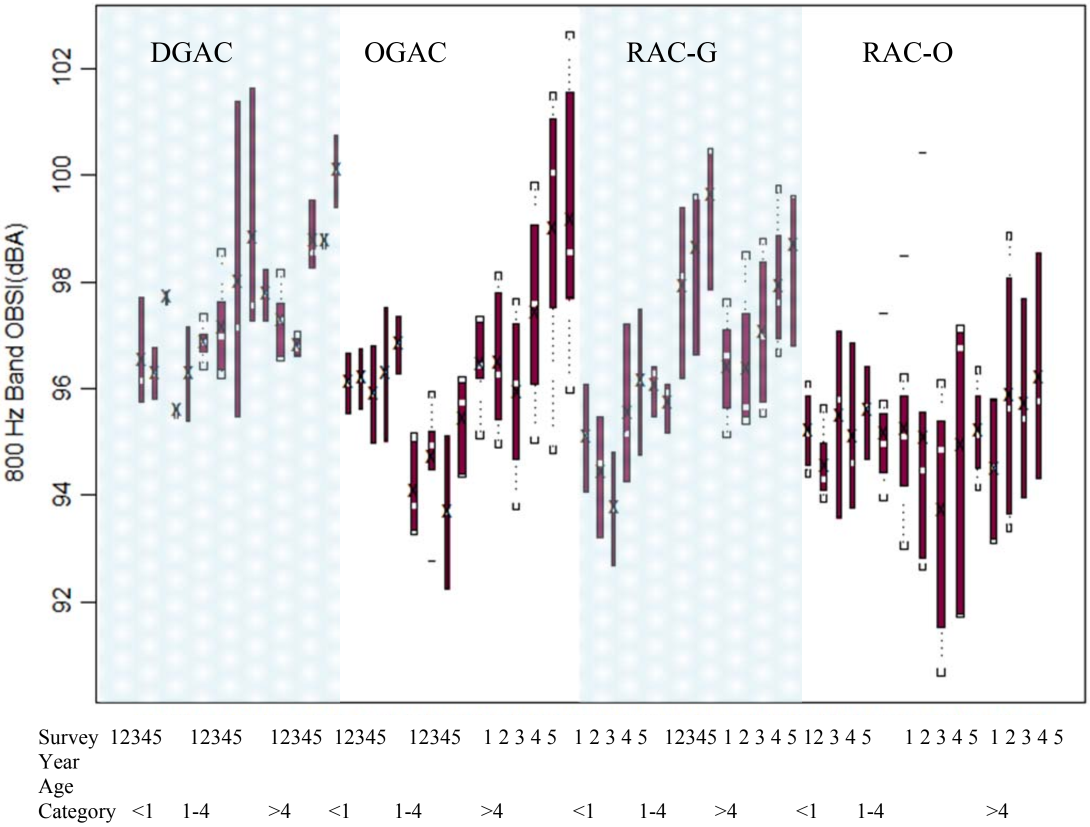
Residual standard error: 1.594 on 180 degrees of freedom; Multiple R-Squared: 0.65.

Appendix B.4: Box Plots and Cumulative Distribution of Noise Reduction for Sound Intensity at Other Frequency Bands

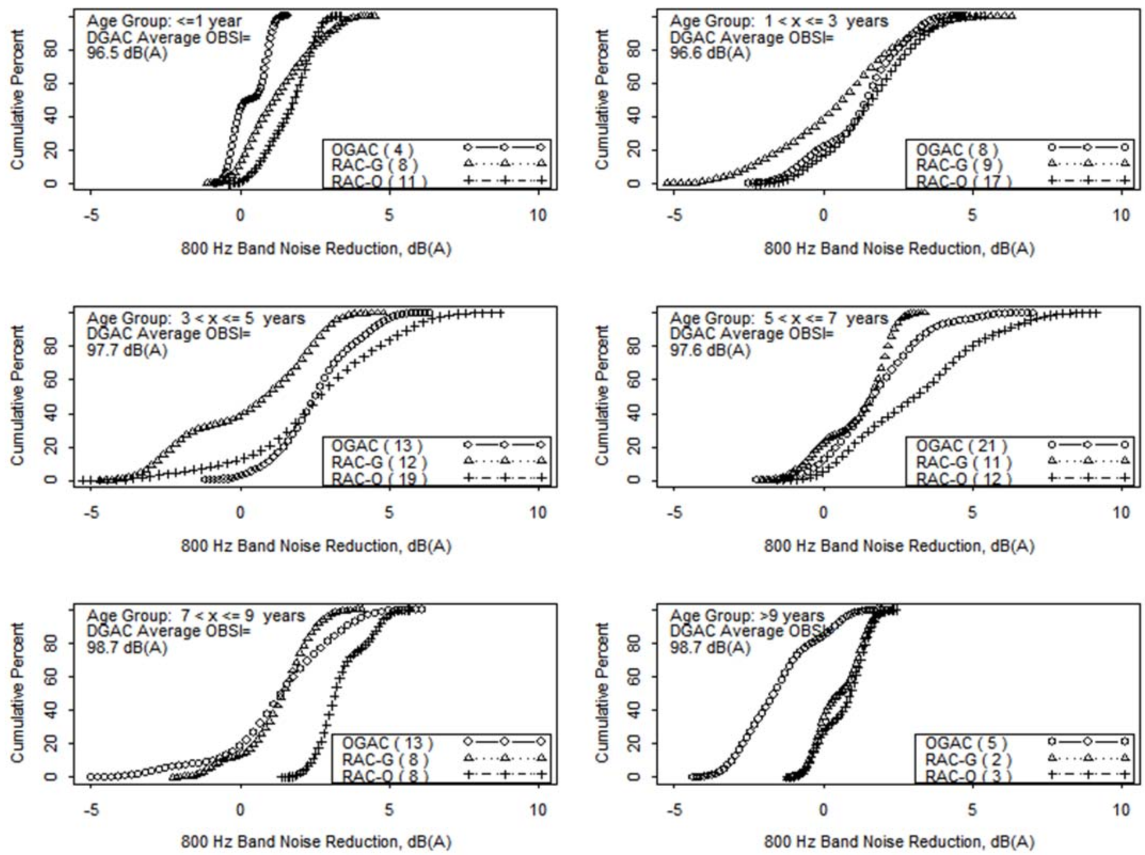


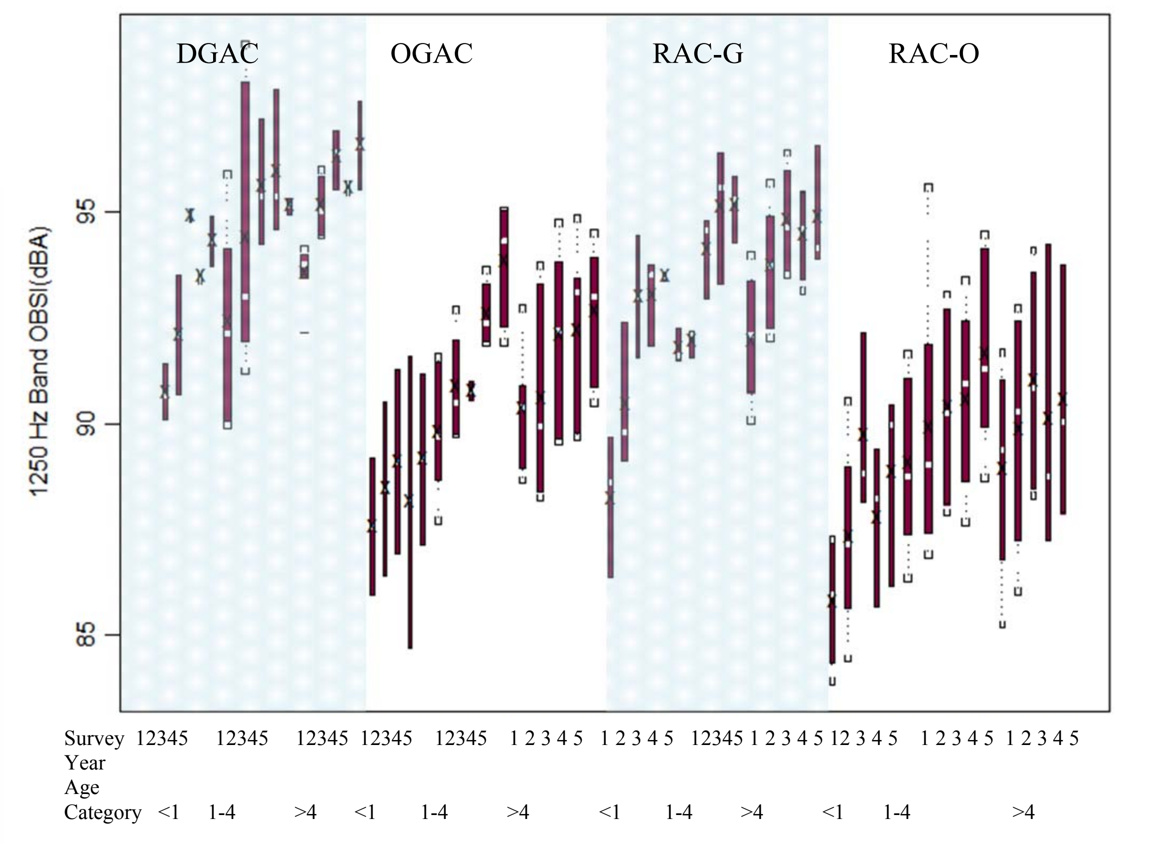


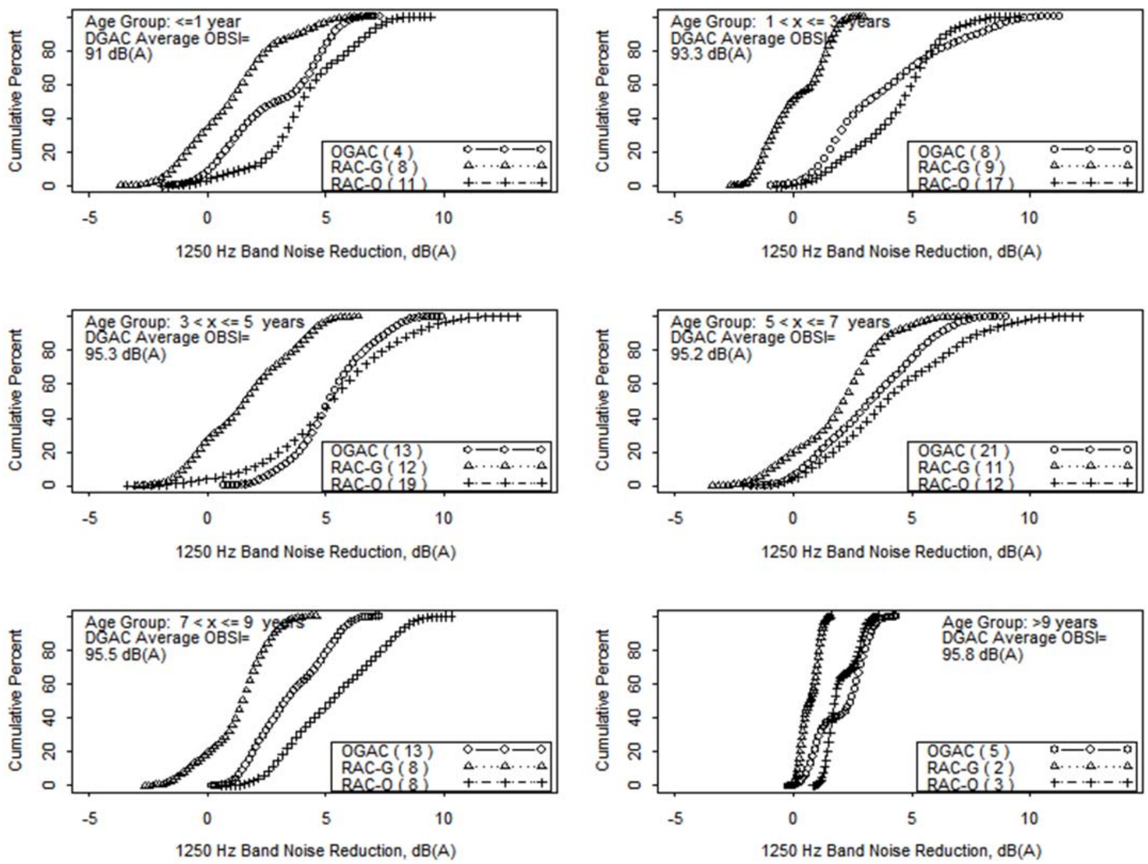
Age Group: <=1 year
DGAC Average OBSI=
89.5 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
90.2 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
91.3 dB(A)
OGAC (13)
RAC-G (12)
RAC-O (19)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
91.4 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (12)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
92.2 dB(A)
OGAC (13)
RAC-G (8)
RAC-O (8)
Age Group: >9 years
DGAC Average OBSI=
94.2 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (3)
Cumulative Percent
630 Hz Band Noise Reduction, dB(A)

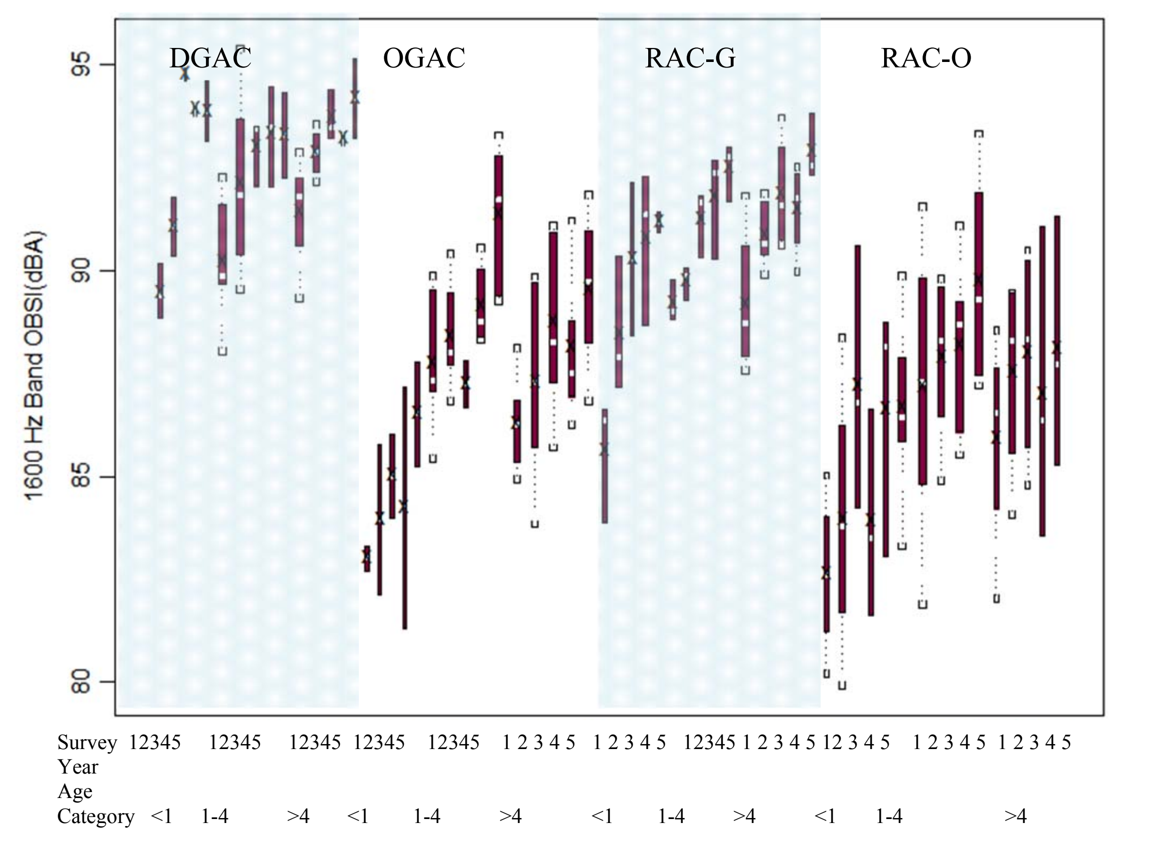


DGAC
OGAC
RAC-G
RAC-O
800 Hz Band OBSI(dBA)
102
100
98
96
94
92
Survey Year Age Category
12345 12345 12345 12345 12345 1 2 3 4 5 1 2 3 4 5 12345 1 2 3 4 5 12 3 4 5 1 2 3 4 5 1 2 3 4 5
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

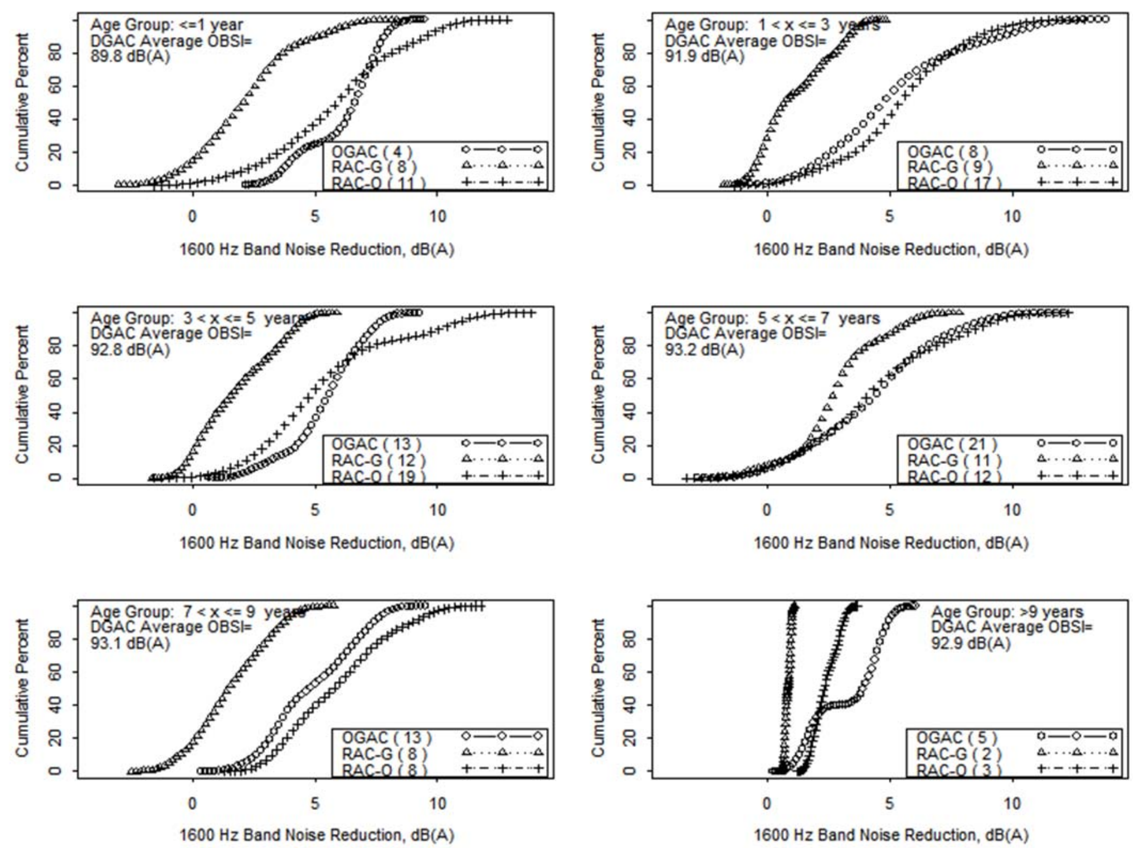

Age Group: <=1 year
DGAC Average OBSI=
96.5 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
96.6 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
97.7 dB(A)
OGAC (13)
RAC-G (12)
RAC-O (19)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
97.6 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (12)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
98.7 dB(A)
OGAC (13)
RAC-G (8)
RAC-O (8)
Age Group: >9 years
DGAC Average OBSI=
98.7 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (3)
Cumulative Percent
800 Hz Band Noise Reduction, dB(A)

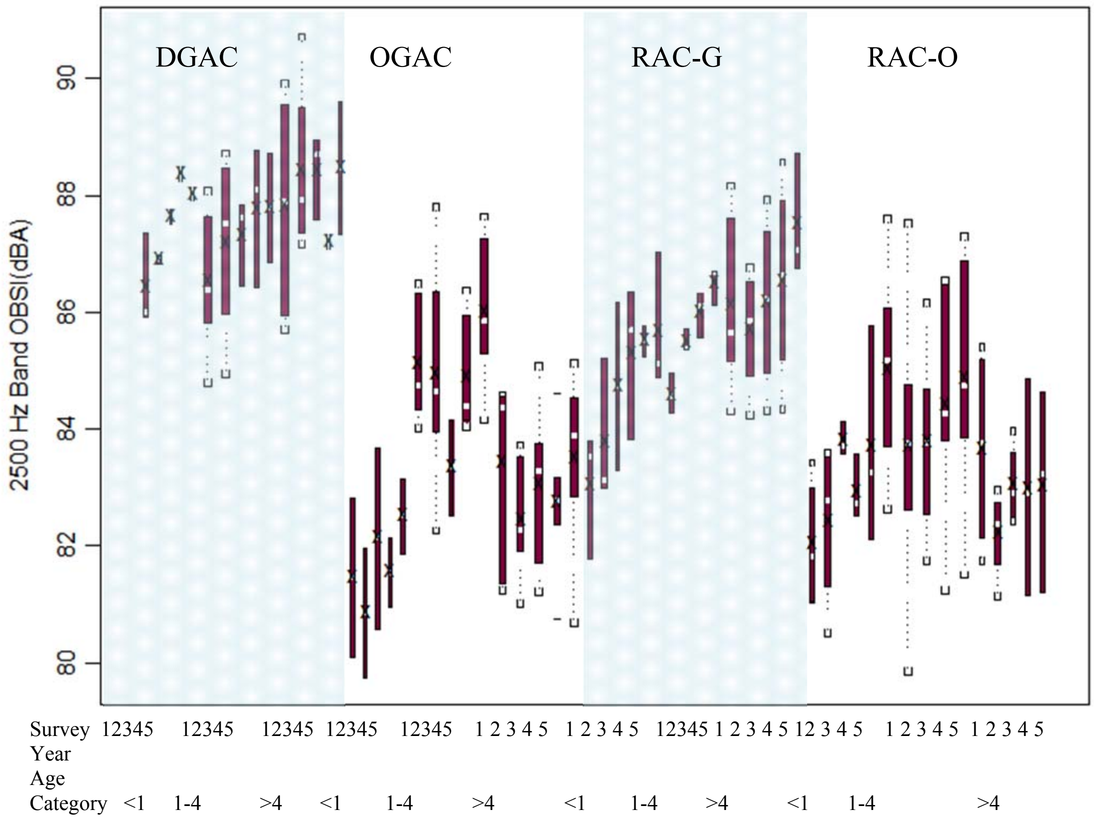

DGAC
OGAC
RAC-G
RAC-O
1250 Hz Band OBSI(dBA)
85
90
95
Survey Year Age Category
12345 12345 12345 12345 12345 1 2 3 4 5 1 2 3 4 5 12345 1 2 3 4 5 12 3 4 5 1 2 3 4 5 1 2 3 4 5
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

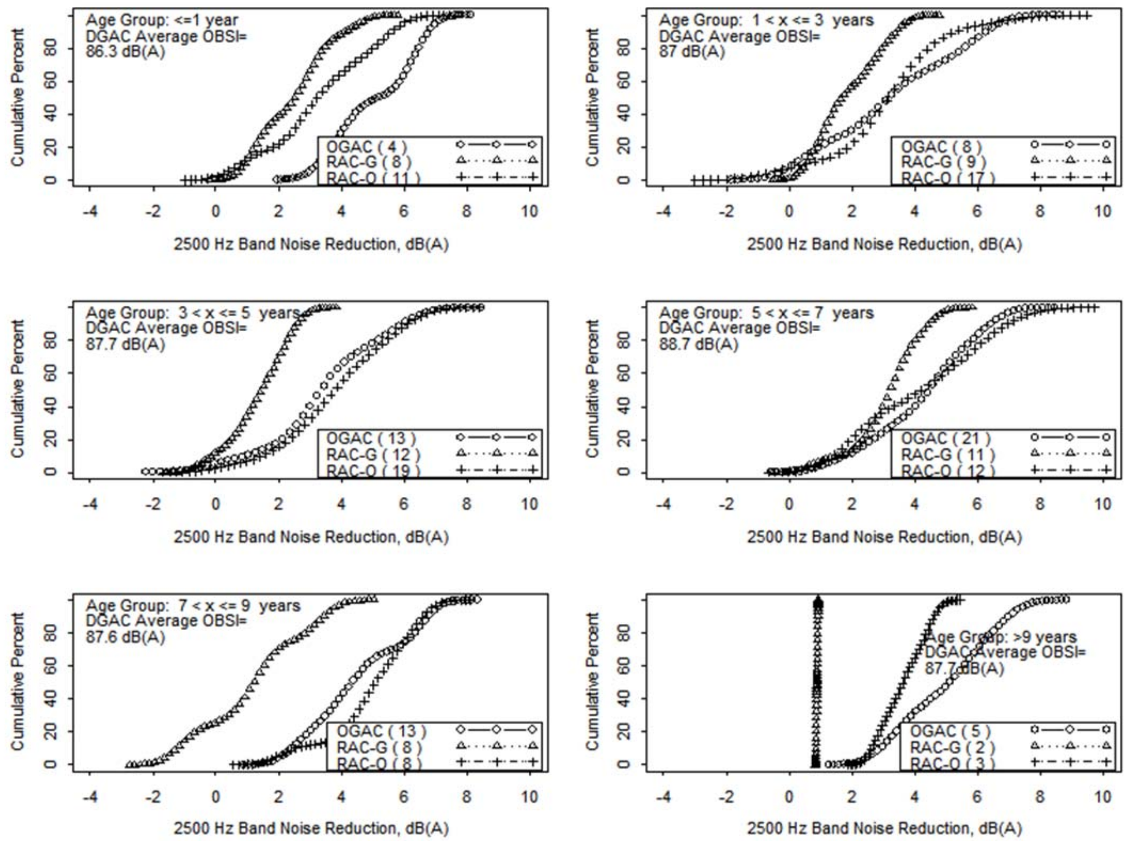

Age Group: <=1 year
DGAC Average OBSI=
91 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
93.3 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
95.3 dB(A)
OGAC (13)
RAC-G (12)
RAC-O (19)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
95.2 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (12)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
95.5 dB(A)
OGAC (13)
RAC-G (8)
RAC-O (8)
Age Group: >9 years
DGAC Average OBSI=
95.8 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (3)
Cumulative Percent
1250 Hz Band Noise Reduction, dB(A)

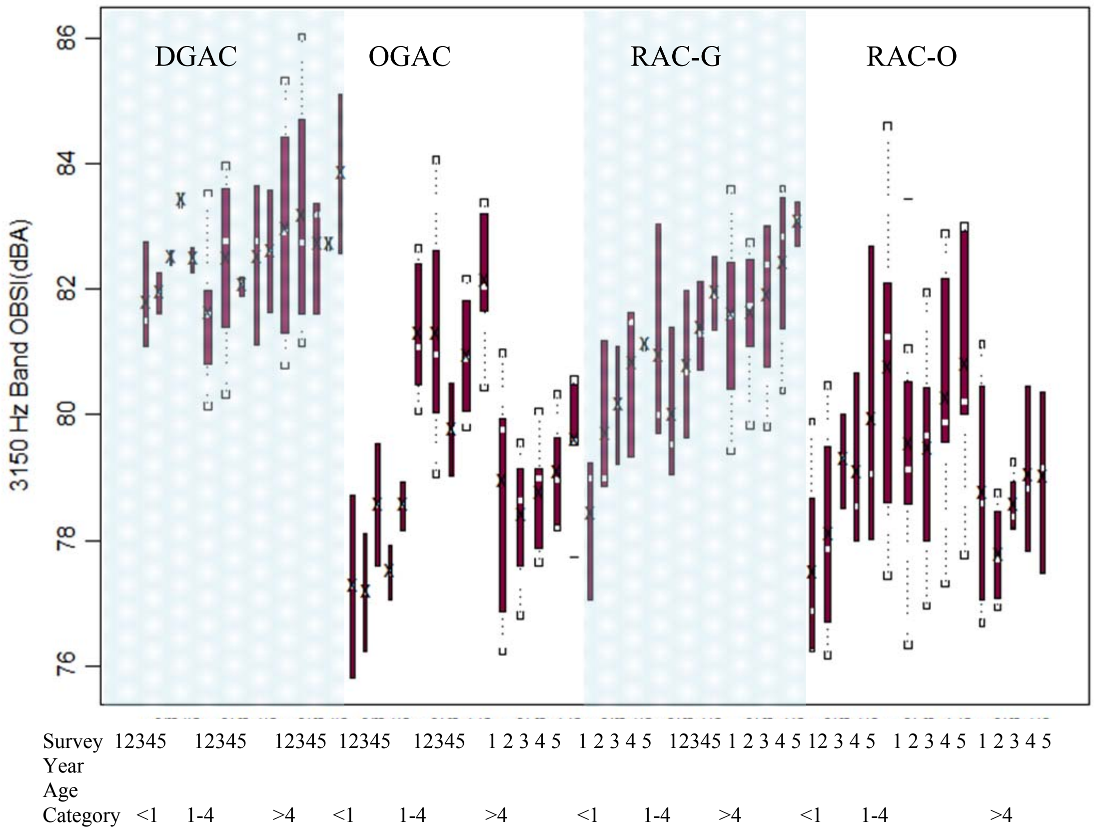


DGAC
OGAC
RAC-G
RAC-O
1600 Hz Band OBSI(dBA)
95
90
85
80
Survey Year
12345 12345 12345 12345 12345 1 2 3 4 5 1 2 3 4 5 12345 1 2 3 4 5 12 3 4 5 1 2 3 4 5 1 2 3 4 5
Age Category
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

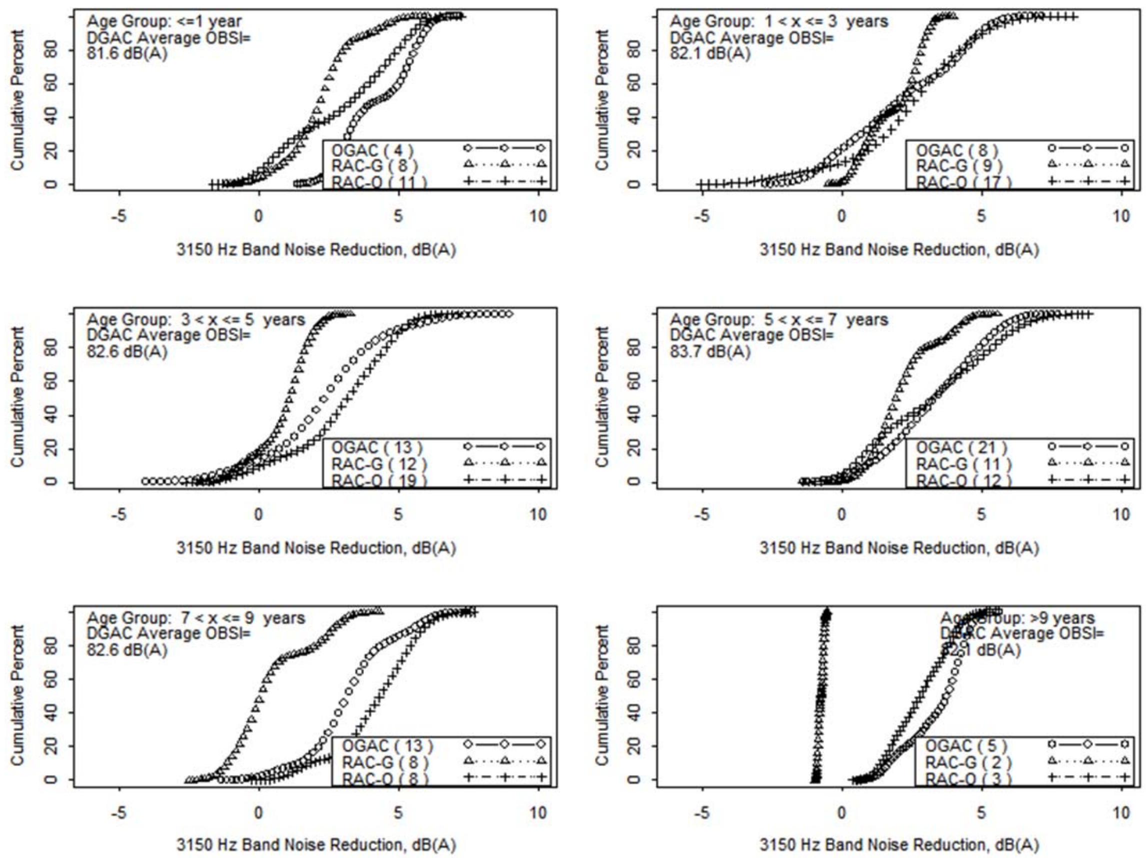

Age Group: <=1 year
DGAC Average OBSI=
89.8 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
91.9 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
92.8 dB(A)
OGAC (13)
RAC-G (12)
RAC-O (19)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
93.2 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (12)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
93.1 dB(A)
OGAC (13)
RAC-G (8)
RAC-O (8)
Age Group: >9 years
DGAC Average OBSI=
92.9 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (3)
Cumulative Percent
1600 Hz Band Noise Reduction, dB(A)


DGAC
OGAC
RAC-G
RAC-O
2500 Hz Band OBSI(dBA)
80
82
84
86
88
90
Survey Year
Age Category
12345 12345 12345 12345 12345 1 2 3 4 5 1 2 3 4 5 12345 1 2 3 4 5 12 3 4 5 1 2 3 4 5 1 2 3 4 5
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

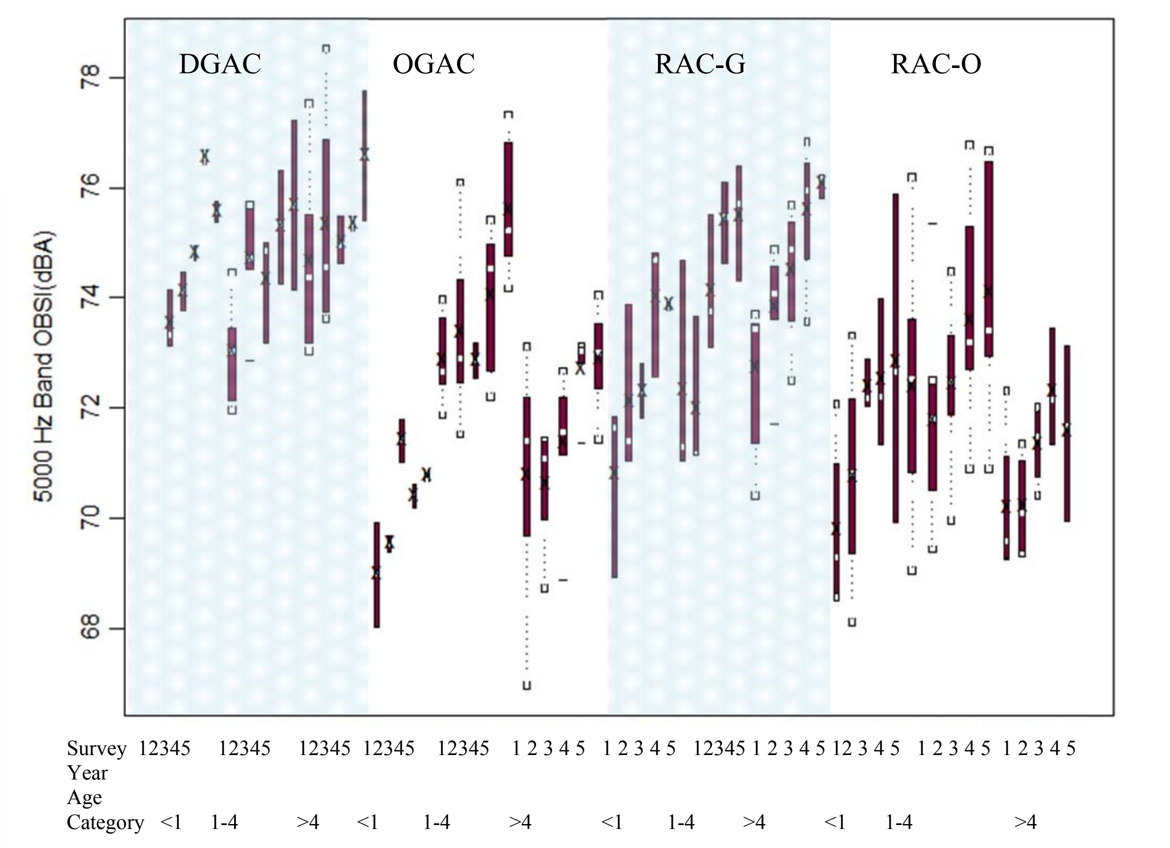

Age Group: <=1 year
DGAC Average OBSI=
86.3 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
87 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
87.7 dB(A)
OGAC (13)
RAC-G (12)
RAC-O (19)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
88.7 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (12)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
87.6 dB(A)
OGAC (13)
RAC-G (8)
RAC-O (8)
Age Group: >9 years
DGAC Average OBSI=
87.7 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (3)
Cumulative Percent
2500 Hz Band Noise Reduction, dB(A)

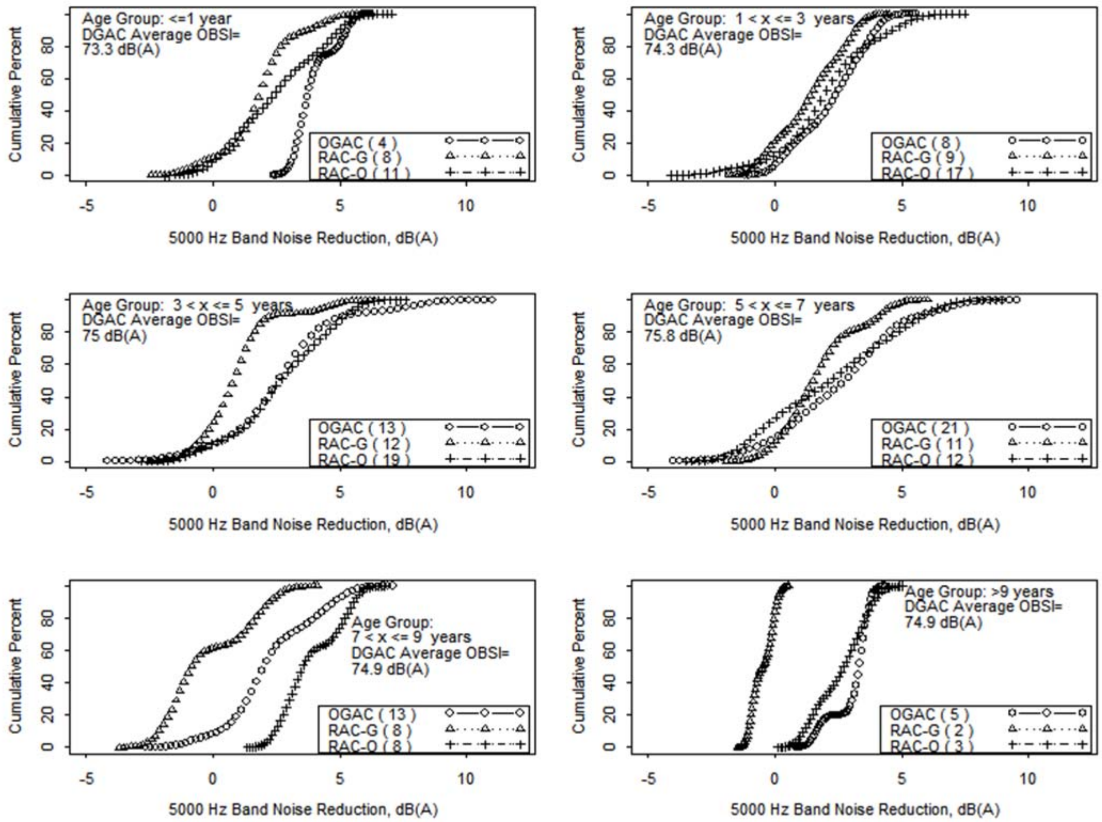


DGAC
OGAC
RAC-G
RAC-O
3150 Hz Band OBSI(dBA)
86
84
82
80
78
76
Survey Year
Age Category
12345 12345 12345 12345 12345 1 2 3 4 5 1 2 3 4 5 12345 1 2 3 4 5 12 3 4 5 1 2 3 4 5 1 2 3 4 5
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4



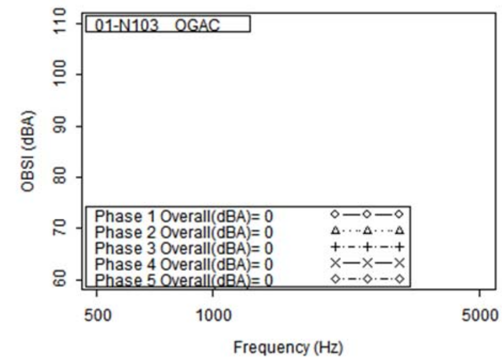
Age Group: <=1 year
DGAC Average OBSI=
81.6 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
82.1 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
82.6 dB(A)
OGAC (13)
RAC-G (12)
RAC-O (19)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
83.7 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (12)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
82.6 dB(A)
OGAC (13)
RAC-G (8)
RAC-O (8)
Age Group: >9 years
DGAC Average OBSI=
OGAC (5)
RAC-G (2)
RAC-O (3)
Cumulative Percent
3150 Hz Band Noise Reduction, dB(A)

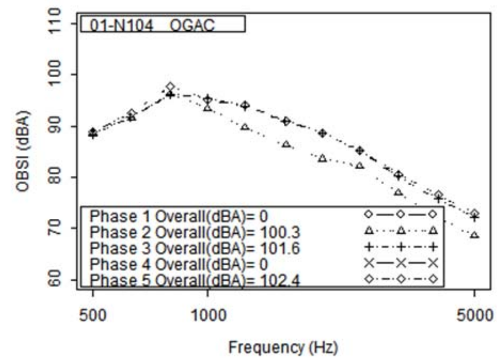

DGAC
OGAC
RAC-G
RAC-O
5000 Hz Band OBSI(dBA)
78
76
74
72
70
68
Survey 12345 12345 12345 12345 12345 1 2 3 4 5 1 2 3 4 5 12345 1 2 3 4 5 12 3 4 5 1 2 3 4 5 1 2 3 4 5
Year
Age
Category <1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

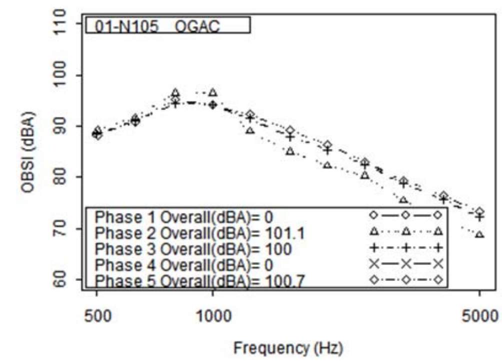


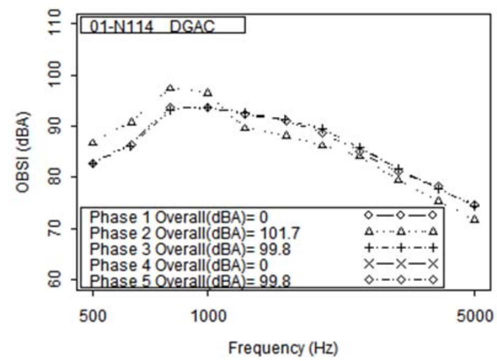
Age Group: <=1 year
DGAC Average OBSI=
73.3 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
74.3 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
75 dB(A)
OGAC (13)
RAC-G (12)
RAC-O (19)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
75.8 dB(A)
OGAC (21)
RAC-G (11)
RAC-O (12)
Age Group:
7 < x <= 9 years
DGAC Average OBSI=
74.9 dB(A)
OGAC (13)
RAC-G (8)
RAC-O (8)
Age Group: >9 years
DGAC Average OBSI=
74.9 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (3)
Cumulative Percent
5000 Hz Band Noise Reduction, dB(A)

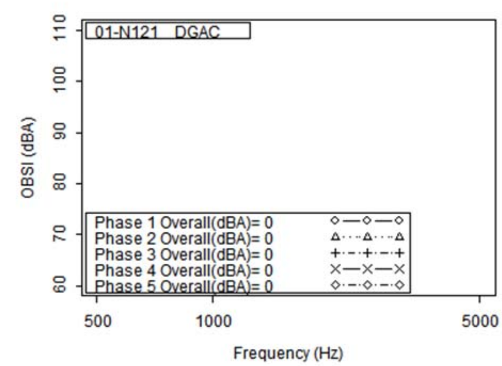
Appendix B.5: Sound Intensity Spectra Measured in Five Years for Each Pavement Section

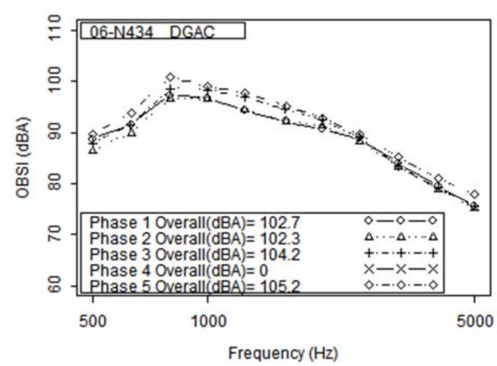


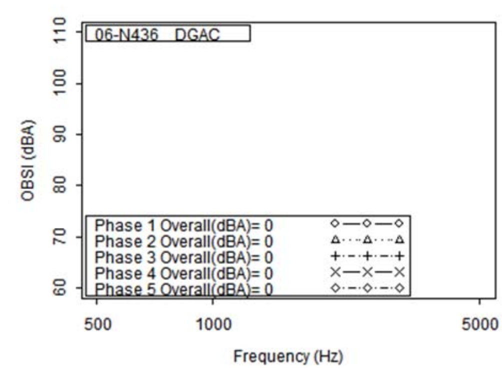


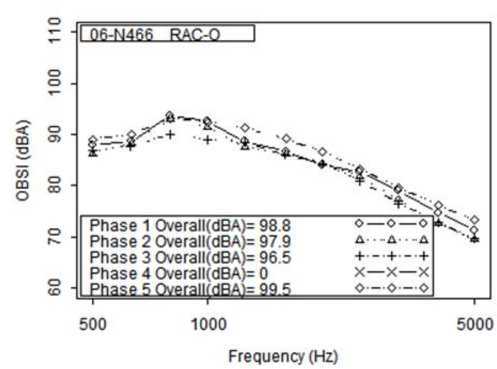


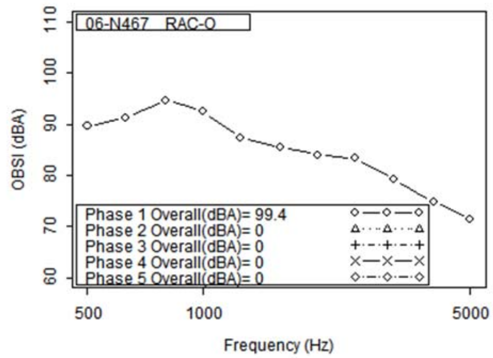


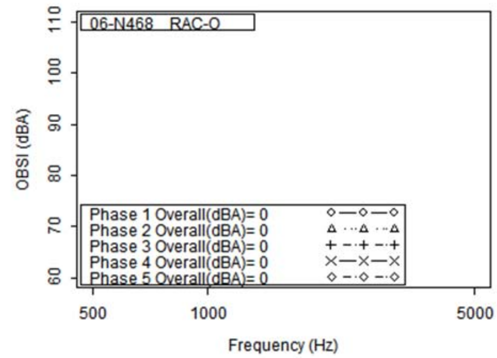


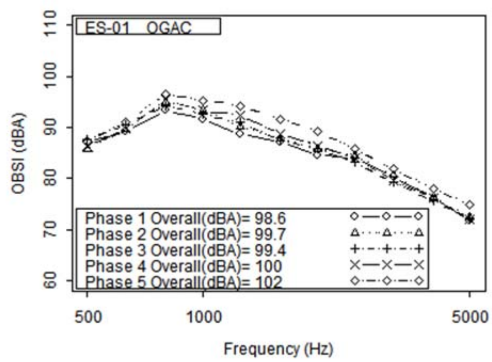


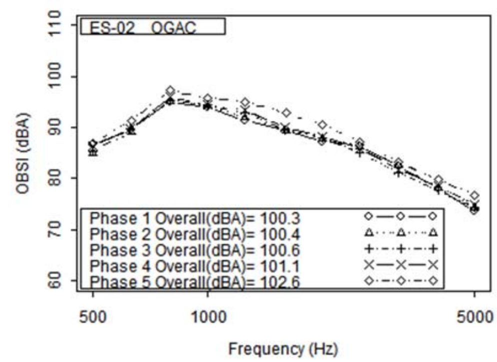


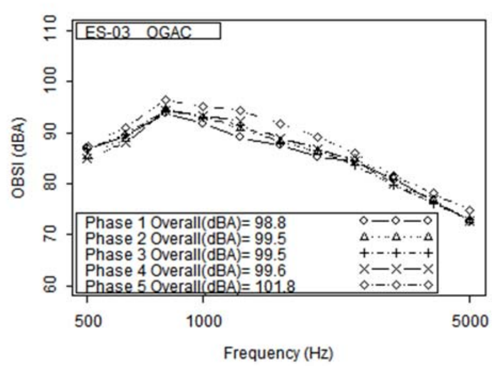


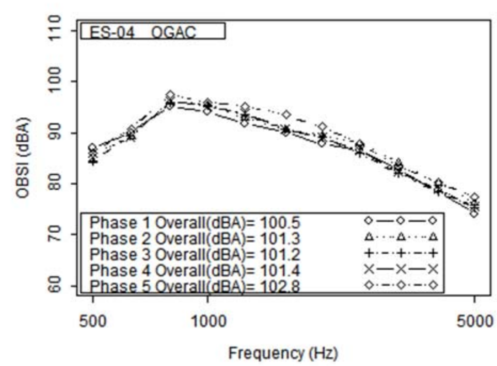

06-N467 RAC-O
OBSI (dBA)
Phase 1 Overall(dBA)= 99.4
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0
Frequency (Hz)

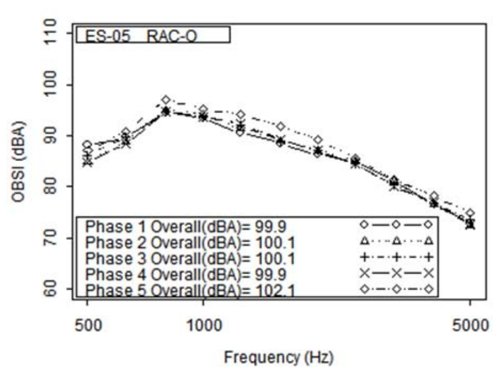

06-N468 RAC-O
OBSI (dBA)
Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0
Frequency (Hz)

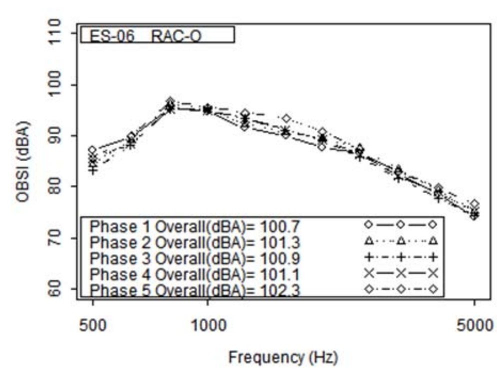

ES-01 OGAC
OBSI (dBA)
Phase 1 Overall(dBA)= 98.6
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 99.4
Phase 4 Overall(dBA)= 100
Phase 5 Overall(dBA)= 102
Frequency (Hz)

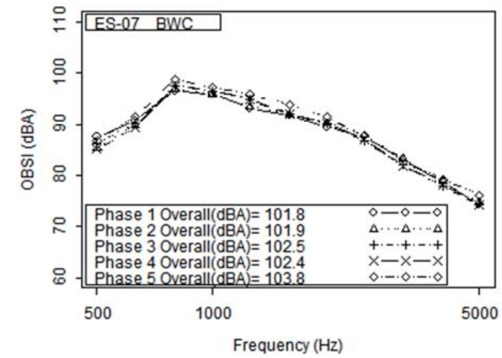

ES-02 OGAC
OBSI (dBA)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 100.6
Phase 4 Overall(dBA)= 101.1
Phase 5 Overall(dBA)= 102.6
Frequency (Hz)

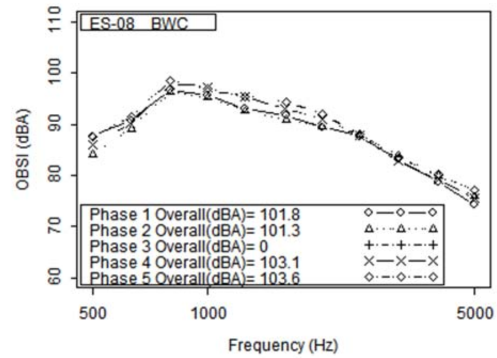

ES-03 OGAC
OBSI (dBA)
Phase 1 Overall(dBA)= 98.8
Phase 2 Overall(dBA)= 99.5
Phase 3 Overall(dBA)= 99.5
Phase 4 Overall(dBA)= 99.6
Phase 5 Overall(dBA)= 101.8
Frequency (Hz)

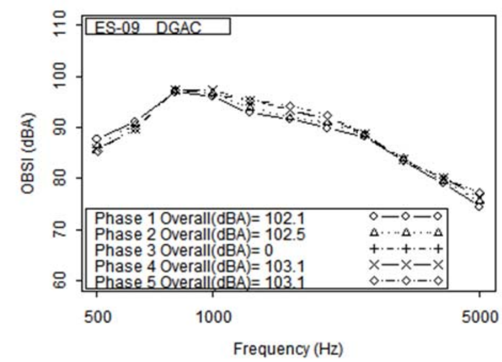

ES-04 OGAC
OBSI (dBA)
Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 101.2
Phase 4 Overall(dBA)= 101.4
Phase 5 Overall(dBA)= 102.8
Frequency (Hz)

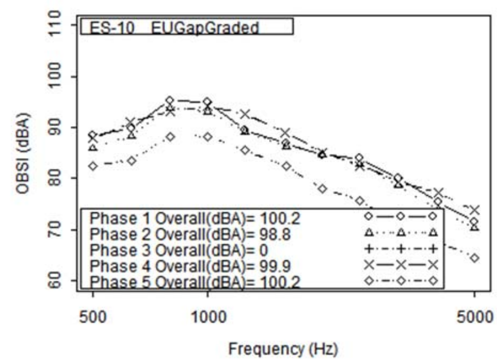

ES-05 RAC-O
OBSI (dBA)
Phase 1 Overall(dBA)= 99.9
Phase 2 Overall(dBA)= 100.1
Phase 3 Overall(dBA)= 100.1
Phase 4 Overall(dBA)= 99.9
Phase 5 Overall(dBA)= 102.1
Frequency (Hz)

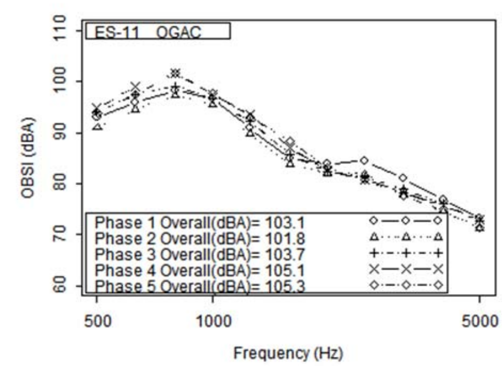

ES-06 RAC-O
OBSI (dBA)
Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 100.9
Phase 4 Overall(dBA)= 101.1
Phase 5 Overall(dBA)= 102.3
Frequency (Hz)

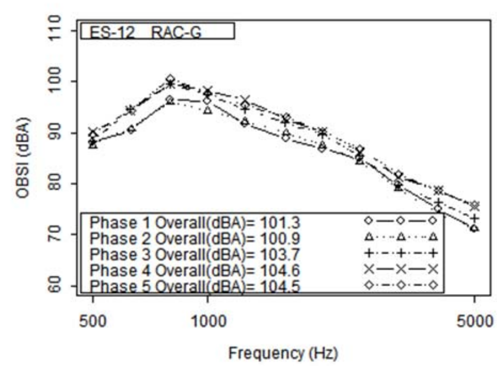

ES-07 BWC
Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 101.9
Phase 3 Overall(dBA)= 102.5
Phase 4 Overall(dBA)= 102.4
Phase 5 Overall(dBA)= 103.8
OBSI (dBA)
Frequency (Hz)

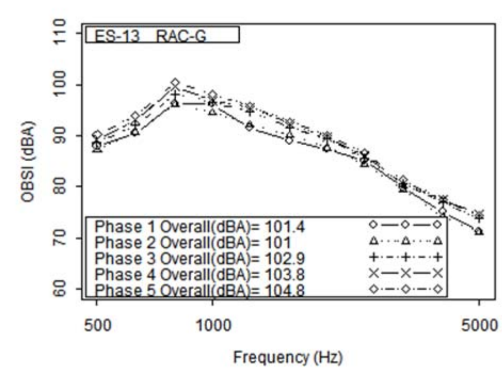

ES-08 BWC
Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 103.1
Phase 5 Overall(dBA)= 103.6
OBSI (dBA)
Frequency (Hz)

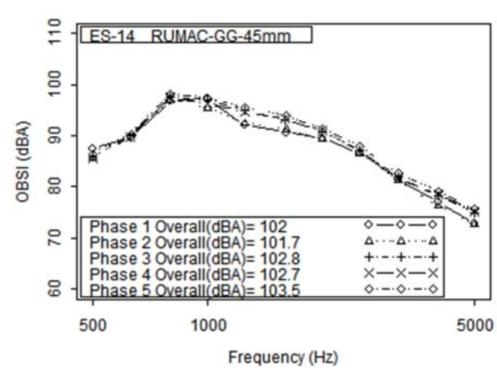

ES-09 DGAC
Phase 1 Overall(dBA)= 102.1
Phase 2 Overall(dBA)= 102.5
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 103.1
Phase 5 Overall(dBA)= 103.1
OBSI (dBA)
Frequency (Hz)

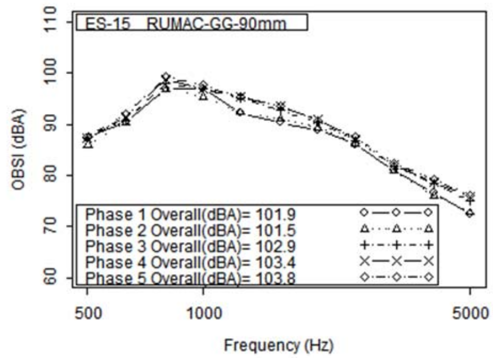

ES-10 EUGapGraded
Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 98.8
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 99.9
Phase 5 Overall(dBA)= 100.2
OBSI (dBA)
Frequency (Hz)

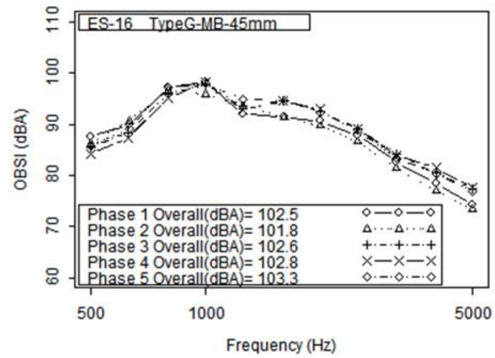

ES-11 OGAC
Phase 1 Overall(dBA)= 103.1
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 103.7
Phase 4 Overall(dBA)= 105.1
Phase 5 Overall(dBA)= 105.3
OBSI (dBA)
Frequency (Hz)

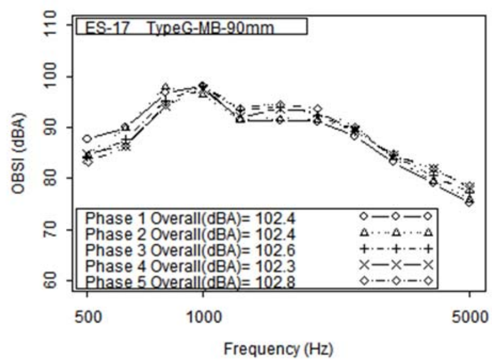

ES-12 RAC-G
Phase 1 Overall(dBA)= 101.3
Phase 2 Overall(dBA)= 100.9
Phase 3 Overall(dBA)= 103.7
Phase 4 Overall(dBA)= 104.6
Phase 5 Overall(dBA)= 104.5
OBSI (dBA)
Frequency (Hz)

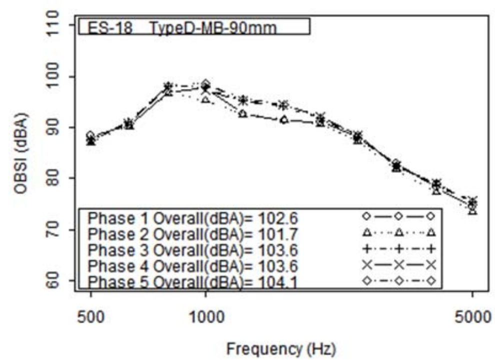

ES-13 RAC-G
Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 101
Phase 3 Overall(dBA)= 102.9
Phase 4 Overall(dBA)= 103.8
Phase 5 Overall(dBA)= 104.8
OBSI (dBA)
Frequency (Hz)

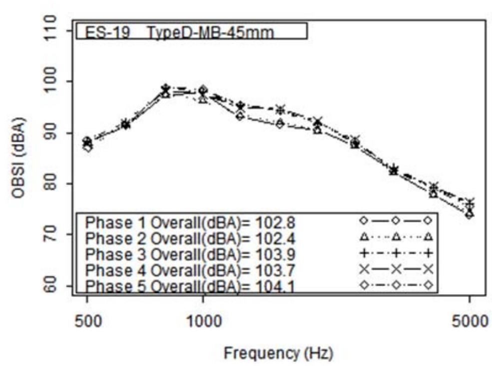

ES-14 RUMAC-GG-45mm
Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 101.7
Phase 3 Overall(dBA)= 102.8
Phase 4 Overall(dBA)= 102.7
Phase 5 Overall(dBA)= 103.5
OBSI (dBA)
Frequency (Hz)

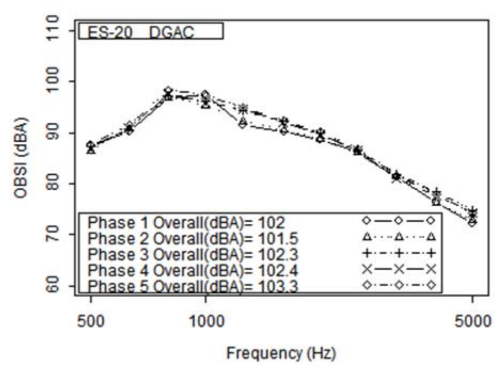

ES-15 RUMAC-GG-90mm
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.9
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 102.9
Phase 4 Overall(dBA)= 103.4
Phase 5 Overall(dBA)= 103.8

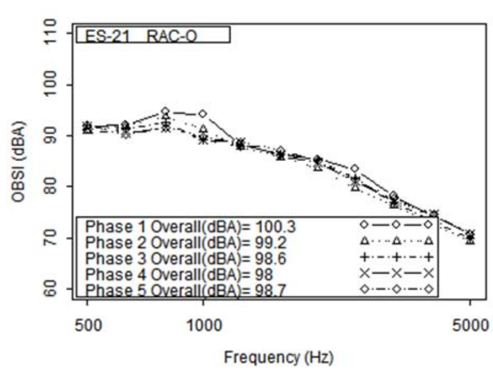

ES-16 TypeG-MB-45mm
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 102.8
Phase 5 Overall(dBA)= 103.3

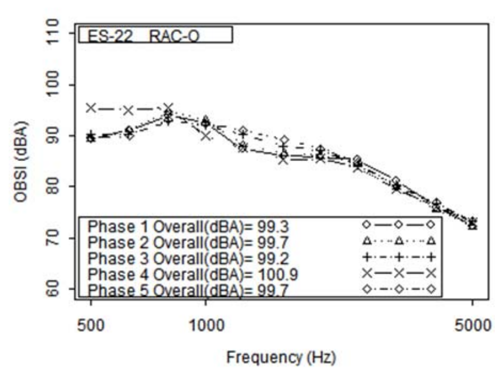

ES-17 TypeG-MB-90mm
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.4
Phase 2 Overall(dBA)= 102.4
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 102.3
Phase 5 Overall(dBA)= 102.8

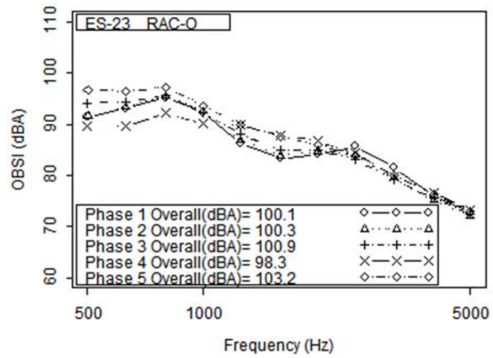

ES-18 TypeD-MB-90mm
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.6
Phase 2 Overall(dBA)= 101.7
Phase 3 Overall(dBA)= 103.6
Phase 4 Overall(dBA)= 103.6
Phase 5 Overall(dBA)= 104.1

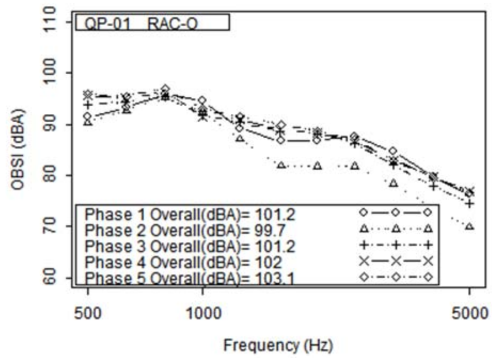

ES-19 TypeD-MB-45mm
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 102.4
Phase 3 Overall(dBA)= 103.9
Phase 4 Overall(dBA)= 103.7
Phase 5 Overall(dBA)= 104.1

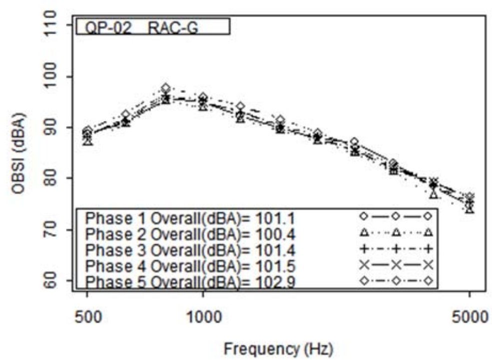

ES-20 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 102.3
Phase 4 Overall(dBA)= 102.4
Phase 5 Overall(dBA)= 103.3

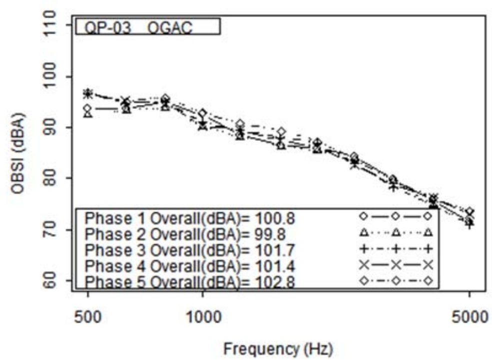

ES-21 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 99.2
Phase 3 Overall(dBA)= 98.6
Phase 4 Overall(dBA)= 98
Phase 5 Overall(dBA)= 98.7

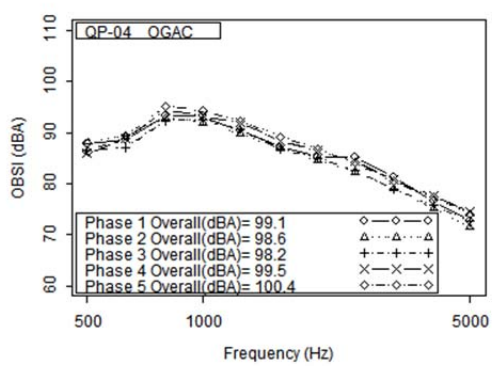

ES-22 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 99.3
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 99.2
Phase 4 Overall(dBA)= 100.9
Phase 5 Overall(dBA)= 99.7

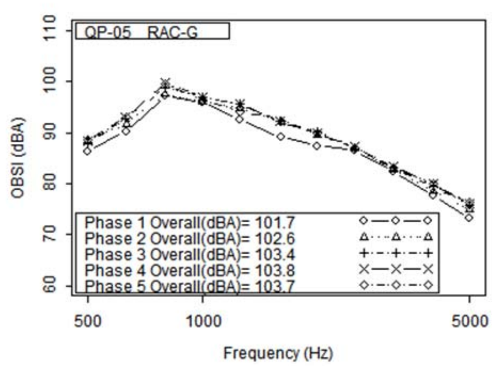

ES-23 RAC-O
Phase 1 Overall(dBA)= 100.1
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 100.9
Phase 4 Overall(dBA)= 98.3
Phase 5 Overall(dBA)= 103.2
OBSI (dBA)
Frequency (Hz)

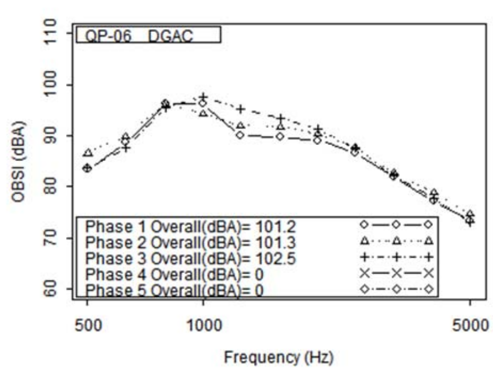

QP-01 RAC-O
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 101.2
Phase 4 Overall(dBA)= 102
Phase 5 Overall(dBA)= 103.1
OBSI (dBA)
Frequency (Hz)

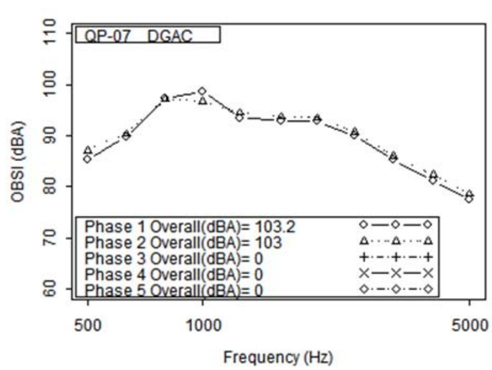

QP-02 RAC-G
Phase 1 Overall(dBA)= 101.1
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 101.4
Phase 4 Overall(dBA)= 101.5
Phase 5 Overall(dBA)= 102.9
OBSI (dBA)
Frequency (Hz)

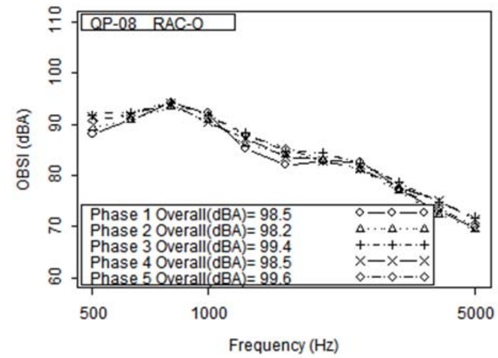

QP-03 OGAC
Phase 1 Overall(dBA)= 100.8
Phase 2 Overall(dBA)= 99.8
Phase 3 Overall(dBA)= 101.7
Phase 4 Overall(dBA)= 101.4
Phase 5 Overall(dBA)= 102.8
OBSI (dBA)
Frequency (Hz)

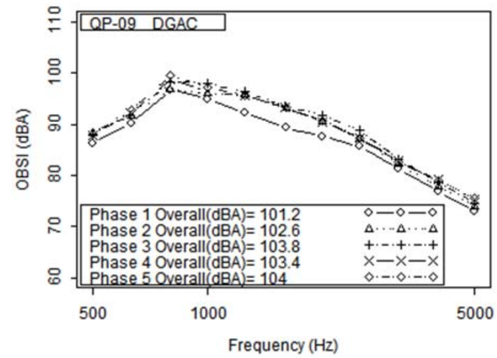

QP-04 OGAC
Phase 1 Overall(dBA)= 99.1
Phase 2 Overall(dBA)= 98.6
Phase 3 Overall(dBA)= 98.2
Phase 4 Overall(dBA)= 99.5
Phase 5 Overall(dBA)= 100.4
OBSI (dBA)
Frequency (Hz)

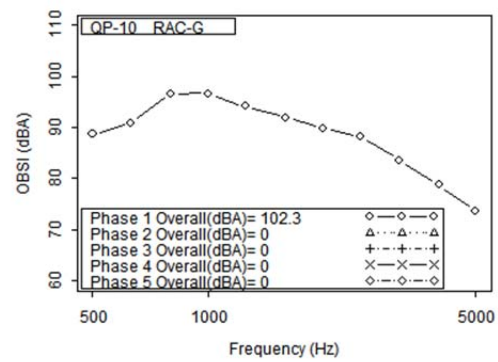

QP-05 RAC-G
Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.6
Phase 3 Overall(dBA)= 103.4
Phase 4 Overall(dBA)= 103.8
Phase 5 Overall(dBA)= 103.7
OBSI (dBA)
Frequency (Hz)

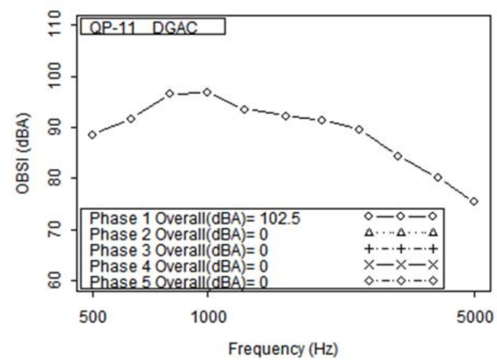

QP-06 DGAC
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 102.5
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0
OBSI (dBA)
Frequency (Hz)

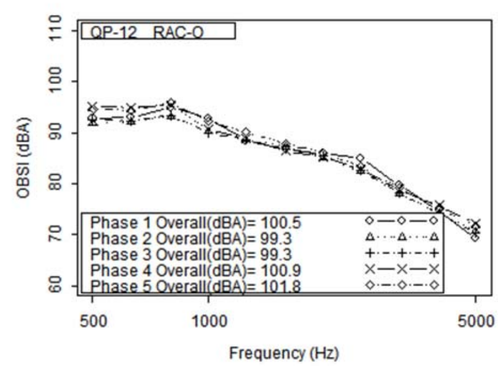

QP-07 DGAC
Phase 1 Overall(dBA)= 103.2
Phase 2 Overall(dBA)= 103
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0
OBSI (dBA)
Frequency (Hz)

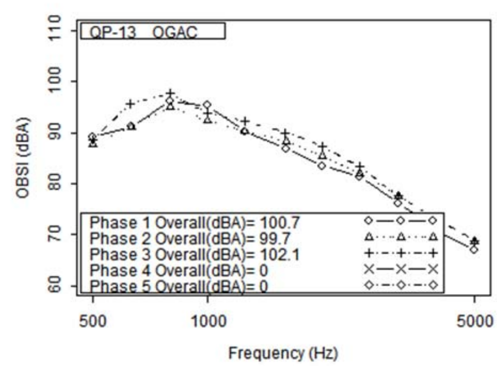

QP-08 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.2
Phase 3 Overall(dBA)= 99.4
Phase 4 Overall(dBA)= 98.5
Phase 5 Overall(dBA)= 99.6

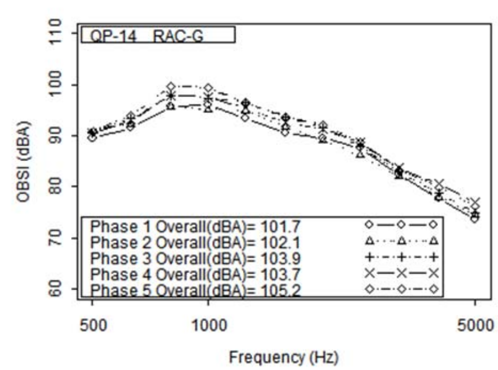

QP-09 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 102.6
Phase 3 Overall(dBA)= 103.8
Phase 4 Overall(dBA)= 103.4
Phase 5 Overall(dBA)= 104

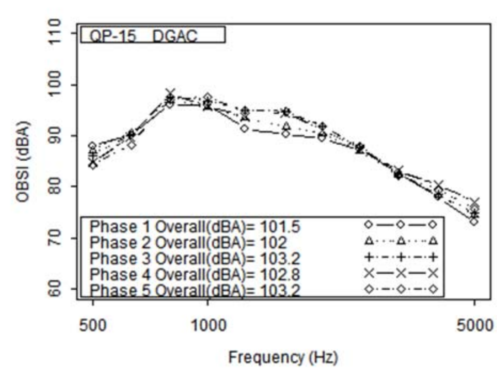

QP-10 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.3
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

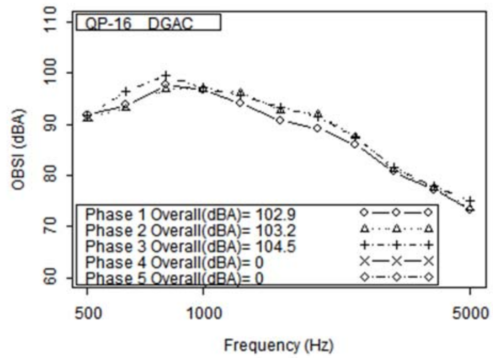

QP-11 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

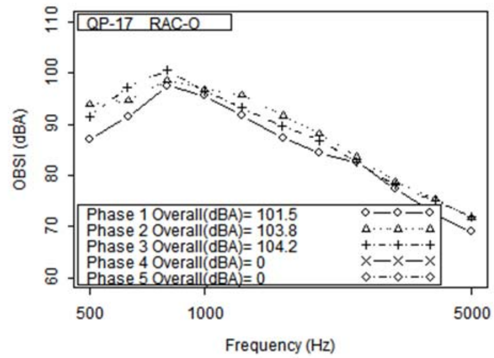

QP-12 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 99.3
Phase 3 Overall(dBA)= 99.3
Phase 4 Overall(dBA)= 100.9
Phase 5 Overall(dBA)= 101.8

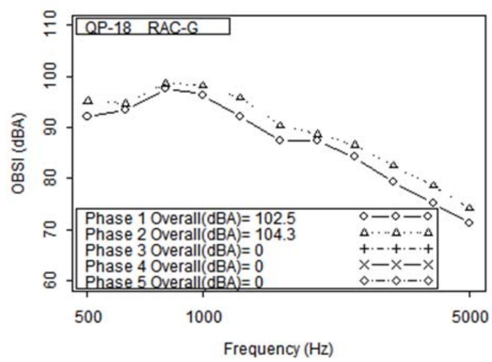

QP-13 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 102.1
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

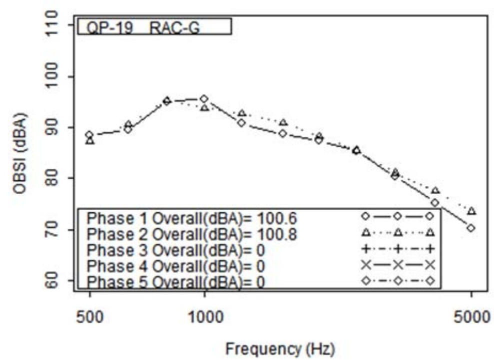

QP-14 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.1
Phase 3 Overall(dBA)= 103.9
Phase 4 Overall(dBA)= 103.7
Phase 5 Overall(dBA)= 105.2

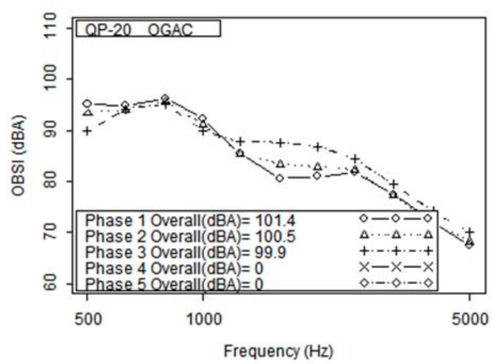

QP-15 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 102
Phase 3 Overall(dBA)= 103.2
Phase 4 Overall(dBA)= 102.8
Phase 5 Overall(dBA)= 103.2

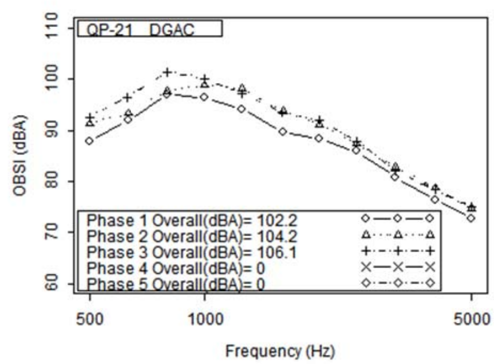

QP-16 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.9
Phase 2 Overall(dBA)= 103.2
Phase 3 Overall(dBA)= 104.5
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

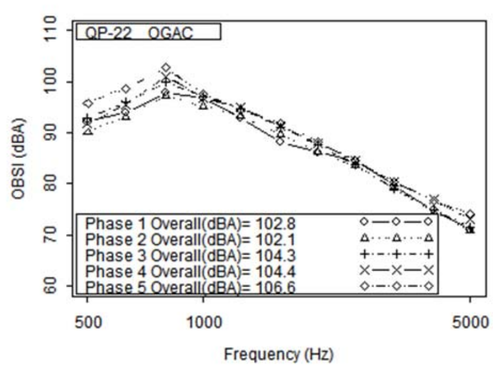

QP-17 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 103.8
Phase 3 Overall(dBA)= 104.2
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

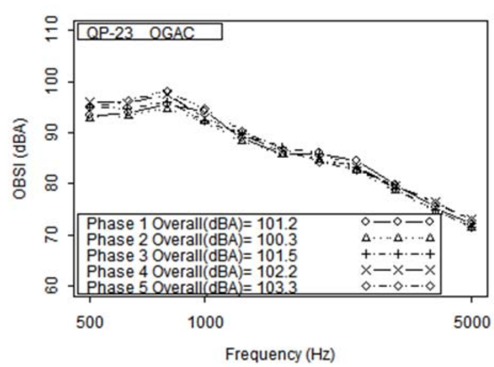

QP-18 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 104.3
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

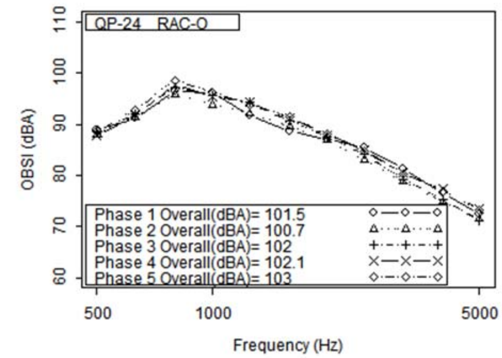

QP-19 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 100.8
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

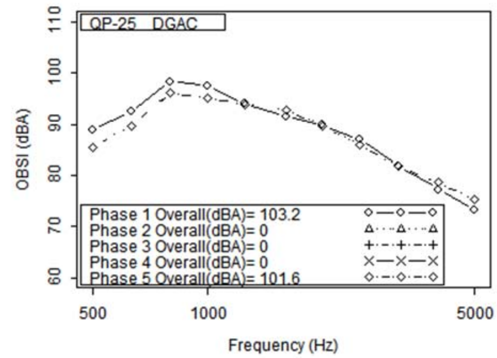

QP-20 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 99.9
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

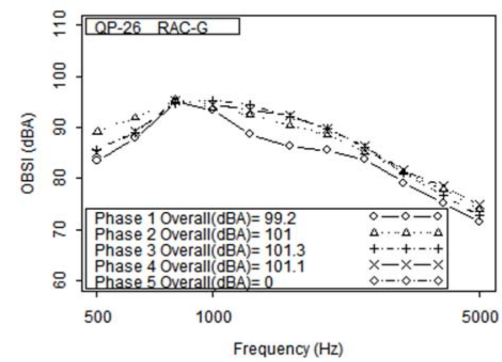

QP-21 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.2
Phase 2 Overall(dBA)= 104.2
Phase 3 Overall(dBA)= 106.1
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

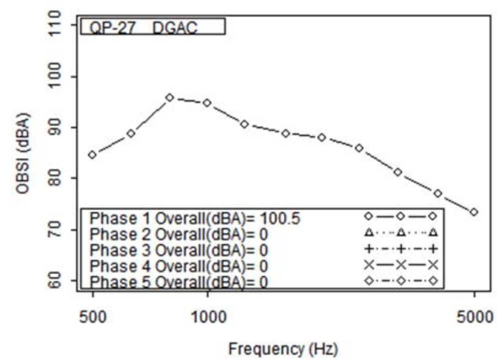

QP-22 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 102.1
Phase 3 Overall(dBA)= 104.3
Phase 4 Overall(dBA)= 104.4
Phase 5 Overall(dBA)= 106.6

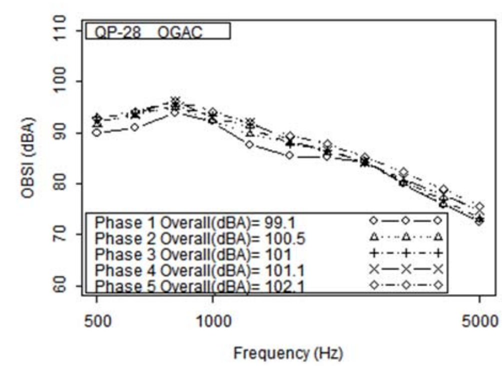

QP-23 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 101.5
Phase 4 Overall(dBA)= 102.2
Phase 5 Overall(dBA)= 103.3

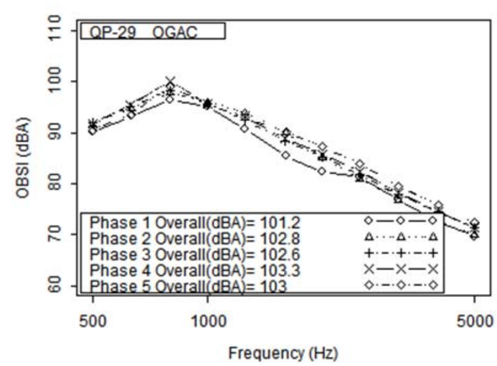

QP-24 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 100.7
Phase 3 Overall(dBA)= 102
Phase 4 Overall(dBA)= 102.1
Phase 5 Overall(dBA)= 103

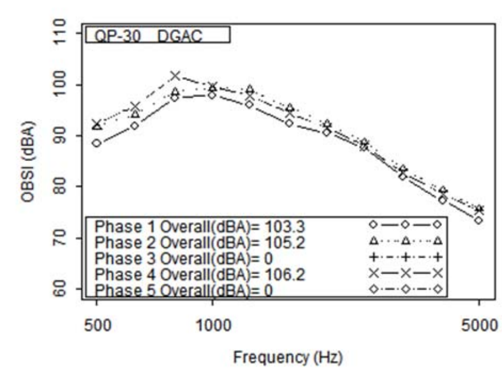

QP-25 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 103.2
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 101.6

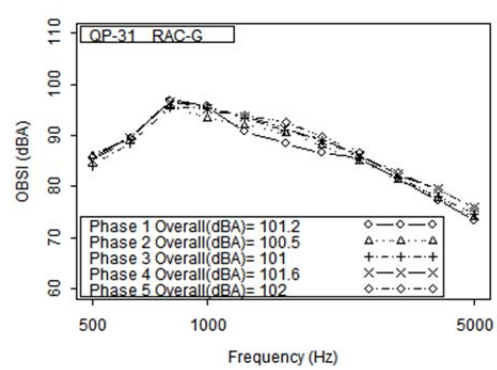

QP-26 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 99.2
Phase 2 Overall(dBA)= 101
Phase 3 Overall(dBA)= 101.3
Phase 4 Overall(dBA)= 101.1
Phase 5 Overall(dBA)= 0

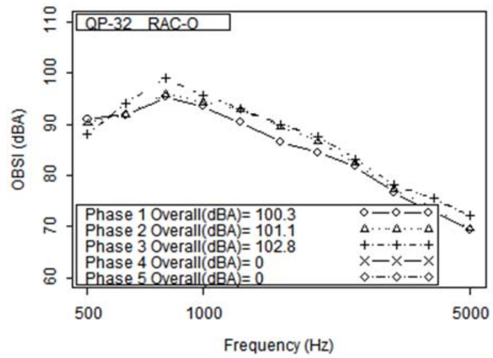

QP-27 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

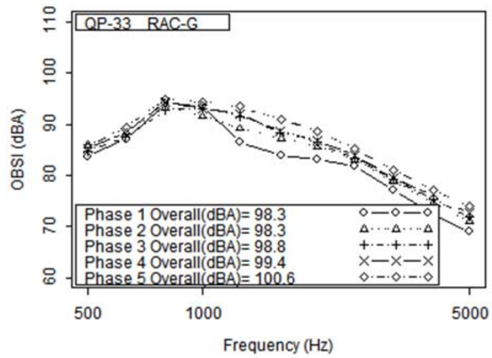

QP-28 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 99.1
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101
Phase 4 Overall(dBA)= 101.1
Phase 5 Overall(dBA)= 102.1

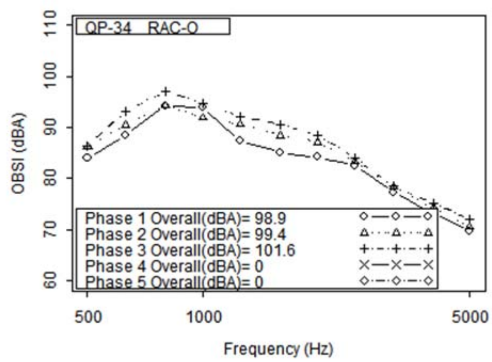

QP-29 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 102.8
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 103.3
Phase 5 Overall(dBA)= 103

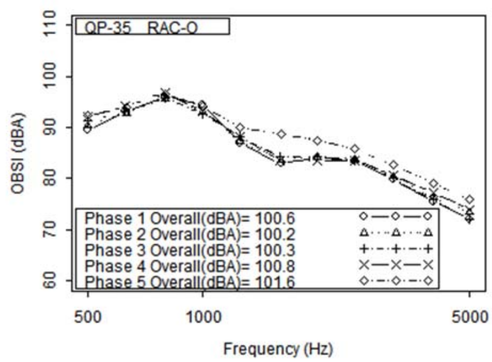

QP-30 DGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 103.3
Phase 2 Overall(dBA)= 105.2
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 106.2
Phase 5 Overall(dBA)= 0

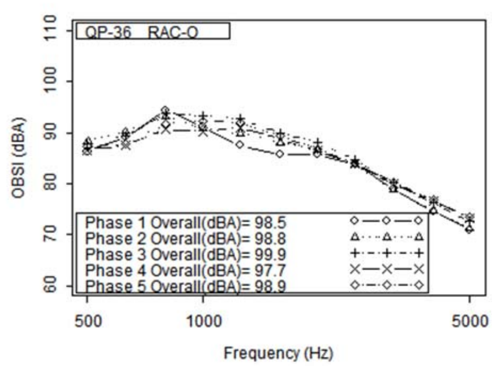

QP-31 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101
Phase 4 Overall(dBA)= 101.6
Phase 5 Overall(dBA)= 102

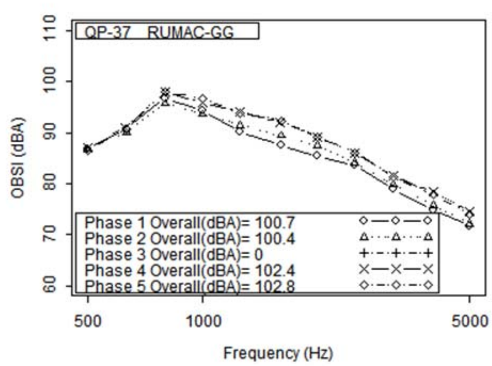

QP-32 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 102.8
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

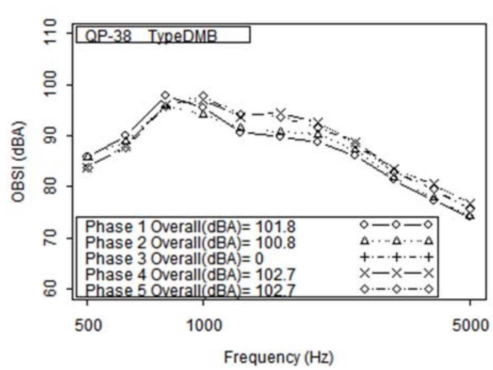

QP-33 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 98.3
Phase 2 Overall(dBA)= 98.3
Phase 3 Overall(dBA)= 98.8
Phase 4 Overall(dBA)= 99.4
Phase 5 Overall(dBA)= 100.6

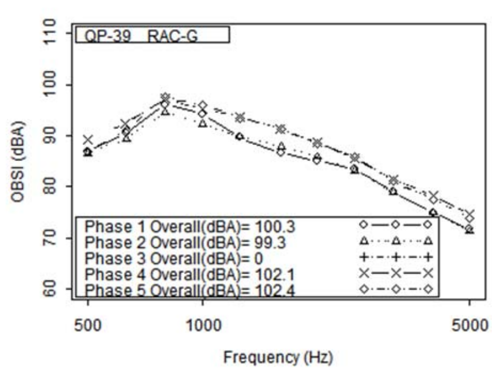

QP-34 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 98.9
Phase 2 Overall(dBA)= 99.4
Phase 3 Overall(dBA)= 101.6
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0

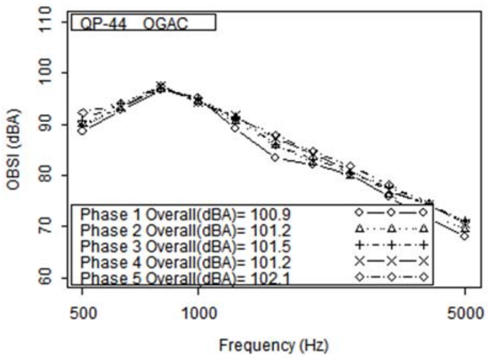

QP-35 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 100.2
Phase 3 Overall(dBA)= 100.3
Phase 4 Overall(dBA)= 100.8
Phase 5 Overall(dBA)= 101.6

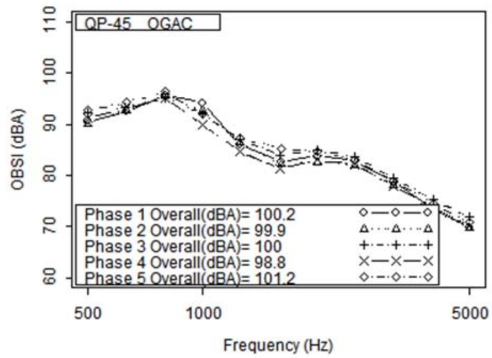

QP-36 RAC-O
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.8
Phase 3 Overall(dBA)= 99.9
Phase 4 Overall(dBA)= 97.7
Phase 5 Overall(dBA)= 98.9

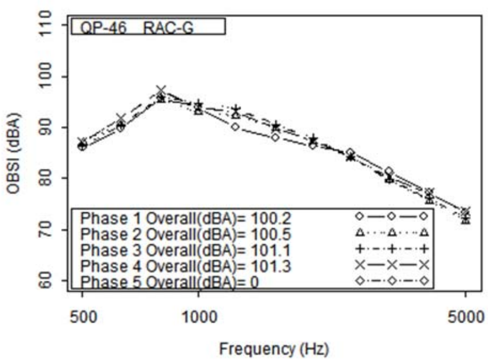

QP-37 RUMAC-GG
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 102.4
Phase 5 Overall(dBA)= 102.8

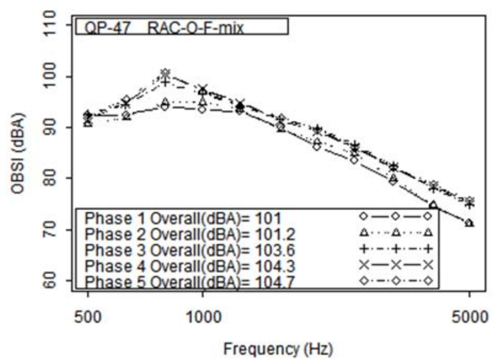

QP-38 TypeDMB
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 100.8
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 102.7
Phase 5 Overall(dBA)= 102.7

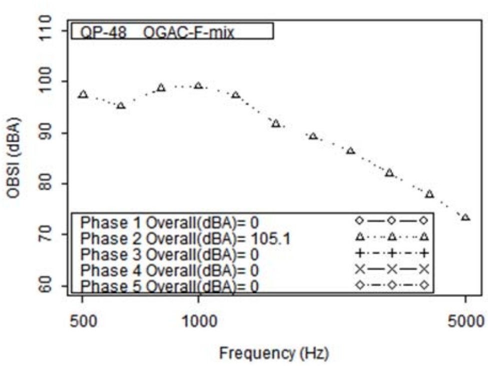

QP-39 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 99.3
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 102.1
Phase 5 Overall(dBA)= 102.4

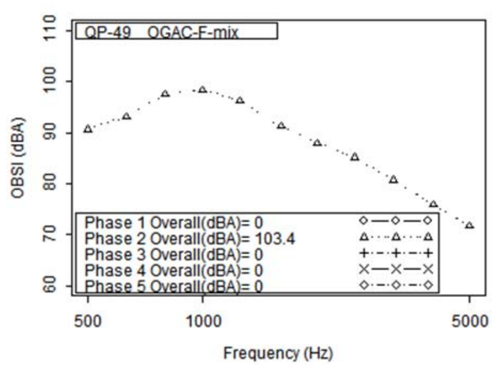

QP-44 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.9
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 101.5
Phase 4 Overall(dBA)= 101.2
Phase 5 Overall(dBA)= 102.1

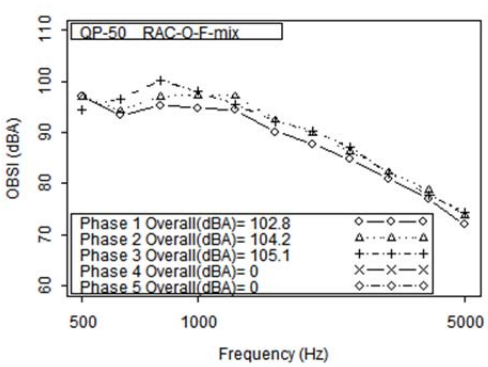

QP-45 OGAC
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 99.9
Phase 3 Overall(dBA)= 100
Phase 4 Overall(dBA)= 98.8
Phase 5 Overall(dBA)= 101.2

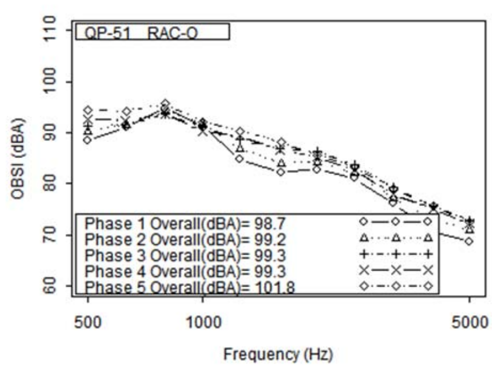

QP-46 RAC-G
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101.1
Phase 4 Overall(dBA)= 101.3
Phase 5 Overall(dBA)= 0

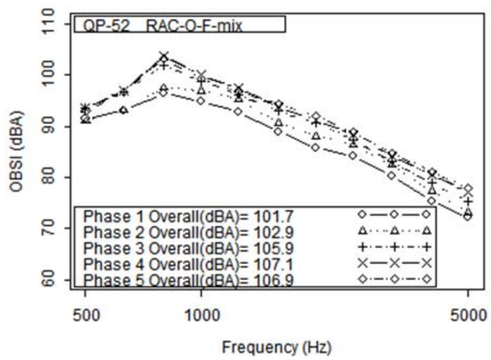

QP-47 RAC-O-F-mix
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 101
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 103.6
Phase 4 Overall(dBA)= 104.3
Phase 5 Overall(dBA)= 104.7


QP-48 OGAC-F-mix
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 105.1
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0


QP-49 OGAC-F-mix
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 103.4
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0


QP-50 RAC-O-F-mix
OBSI (dBA)
Frequency (Hz)
Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 104.2
Phase 3 Overall(dBA)= 105.1
Phase 4 Overall(dBA)= 0
Phase 5 Overall(dBA)= 0


QP-51 RAC-O
OBSI (dBA)
Frequency (Hz)
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


QP-52 RAC-O-F-mix
OBSI (dBA)
Frequency (Hz)
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